CENTER FOR LUNAR SCIENCE AND EXPLORATION
vitally impacting the future – today

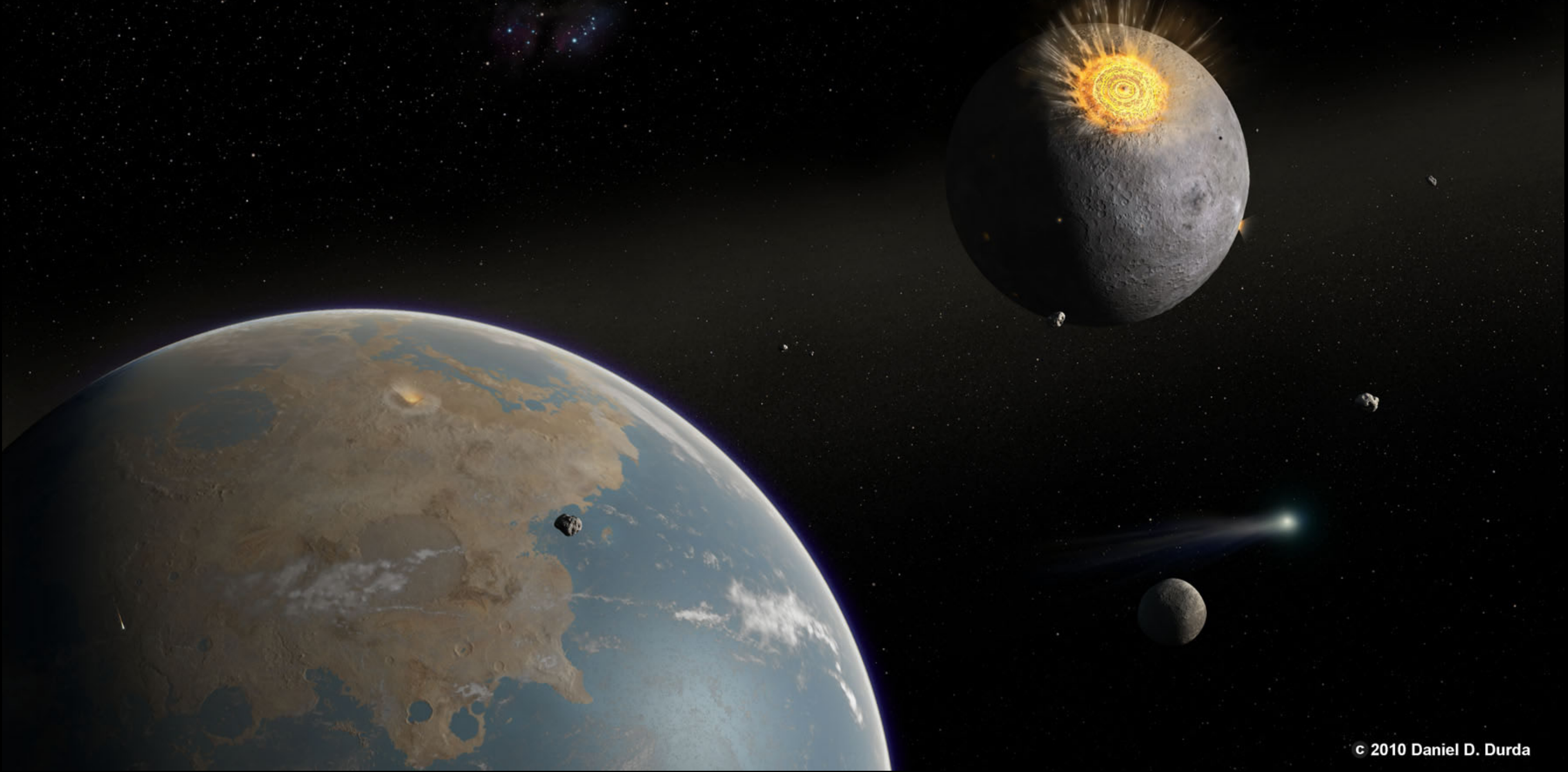
Introduction to Lunar Geology

with notes about those issues affecting ISRU

LPI

SERVI

David A. Kring
Lunar and Planetary Institute, Houston TX



The Goal for Today's Lecture

January 20, 2020

- The goal of today's lecture is to provide enough information about lunar geology so that differences between that geology and more familiar terrestrial geologic processes are understood.
- Lunar geological processes produced a different sequence of rock types (or lithologies) with a unique distribution.
- That, in turn, affects the types of potential ISRU reservoirs that exist on the Moon and their locations.

Format: ~50 minutes of lecture + ~30 minutes of discussion.

The Giant Impact Hypothesis for the Formation of the Earth-Moon System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Origin of the Moon

Historical models include:
- Fission
- Co-accretion
- Capture
- Disintegrative capture
- Giant impact

Models need to contend with:
- Lunar mass
- Angular momentum
- Volatile element depletion
- Fe depletion
- O isotopes
- Magma ocean

In the mid-1970's the giant impact hypothesis emerged (Hartmann & Davis, 1974; Cameron & Ward, 1976) and, in the mid-1980's it gained traction when computational capabilities made it possible to model.

The Giant Impact Hypothesis for the Formation of the Earth-Moon System

Canonical Model

An impactor, approximately half the diameter of the Earth (twice the diameter of the Moon) impacts the proto-Earth at an angle of ~45°.

The impact ejects debris into an orbiting disk, from which the Moon accretes.

The core of the impacting body merges with that of the Earth.

Today, compositional differences between the Moon and Earth, or lack thereof among silicate portions of each body, are among the criteria being used to test the giant impact hypothesis.

Canonical impactor mass ~0.1 to 0.2 M_E. For reference, M_M = 0.012M_E.

The Giant Impact Hypothesis for the Formation of the Earth-Moon System

Exploring Parameter Space

Canup (Science 2012) suggested an impact of a much larger body (similar in mass to the proto-Earth) hitting at a much lower velocity (i.e., less than the present-day escape velocity of 11 km/s).

Ćuk & Stewart (Science 2012) favor impacts with double the kinetic energy; i.e., with impact velocities of ~1.5 to ~2.5 V_{esc} (e.g., 20 km/s) and an impactor mass of ~0.05M_E. A head-on or slightly retrograde impact seems more likely.

Reufer et al. (Icarus 2012) suggest a high impact velocity (1.20 to 1.25 V_{esc}) and steep impact angle (30 to 35°).

The Giant Impact Hypothesis for the Formation of the Earth-Moon System

Relevance to ISRU

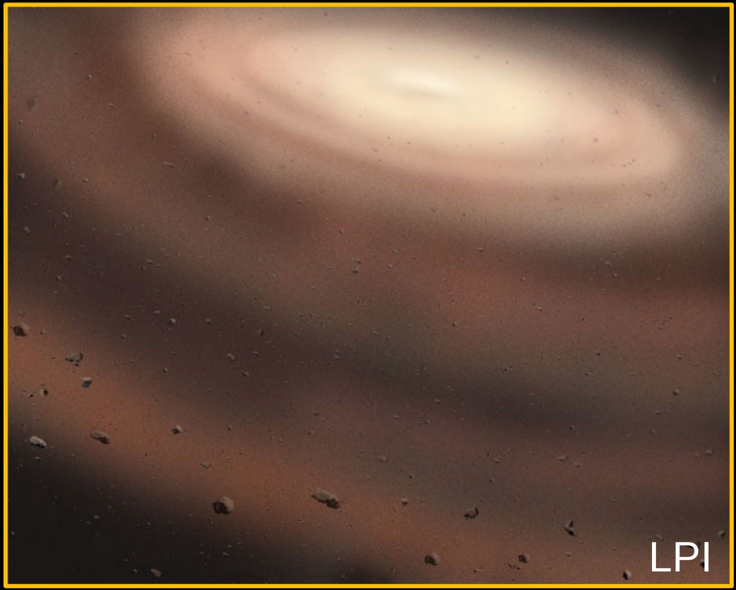
The giant impact produced a Moon with a bulk composition similar to a volatile-depleted version of the Earth's mantle rather than that of a chondritic asteroid.

The giant impact also produced a very hot Moon, which was surrounded by a magma ocean that mineralogically differentiated, producing a chemically-stratified Moon.

Because the Moon lacks plate tectonics, that chemical stratification persists today.

Timing of Proto-Earth Accretion

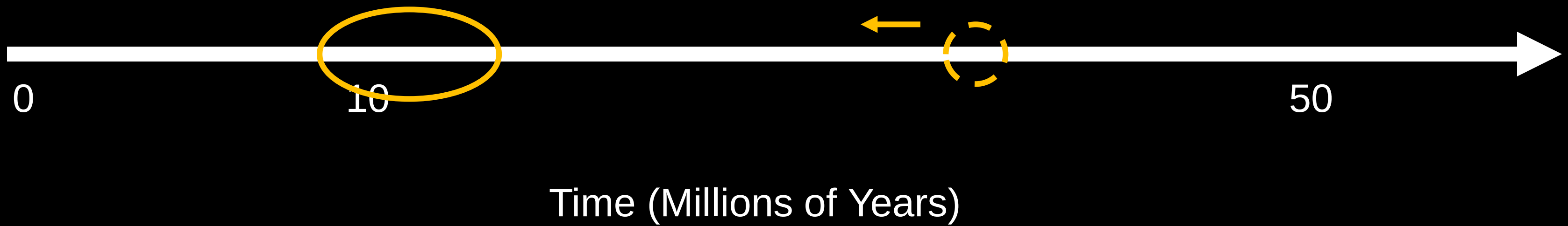
For the purposes of today's discussion, time zero (0) is when the first solids in the Solar System formed, as measured in primitive chondritic meteorites with rocky components that formed in a solar nebula.



Earth Accretes

≤33 Myr (e.g., Kleine et al., 2002)

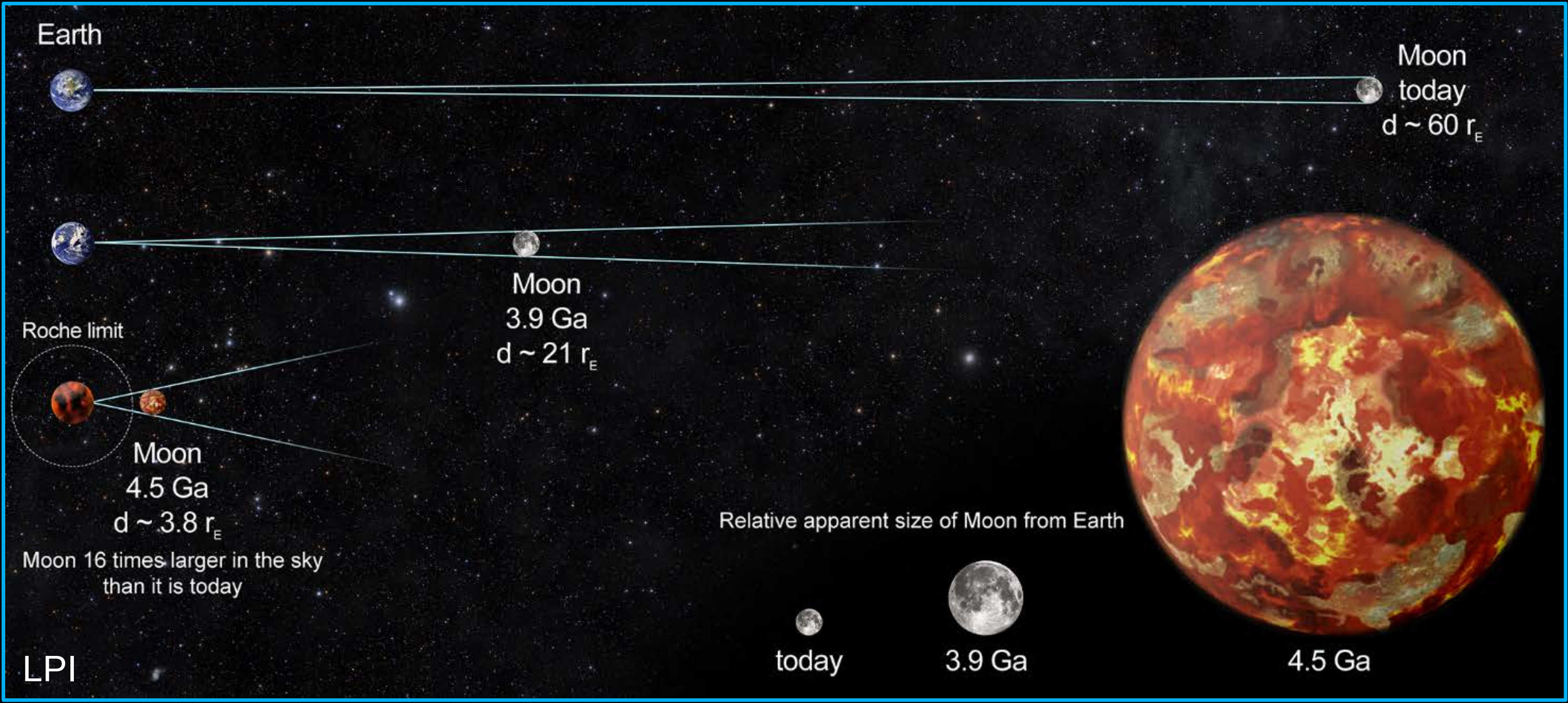
possibly ~10 - 15 Myr (e.g., Halliday & Kleine, 2006)



Timing of Giant Impact

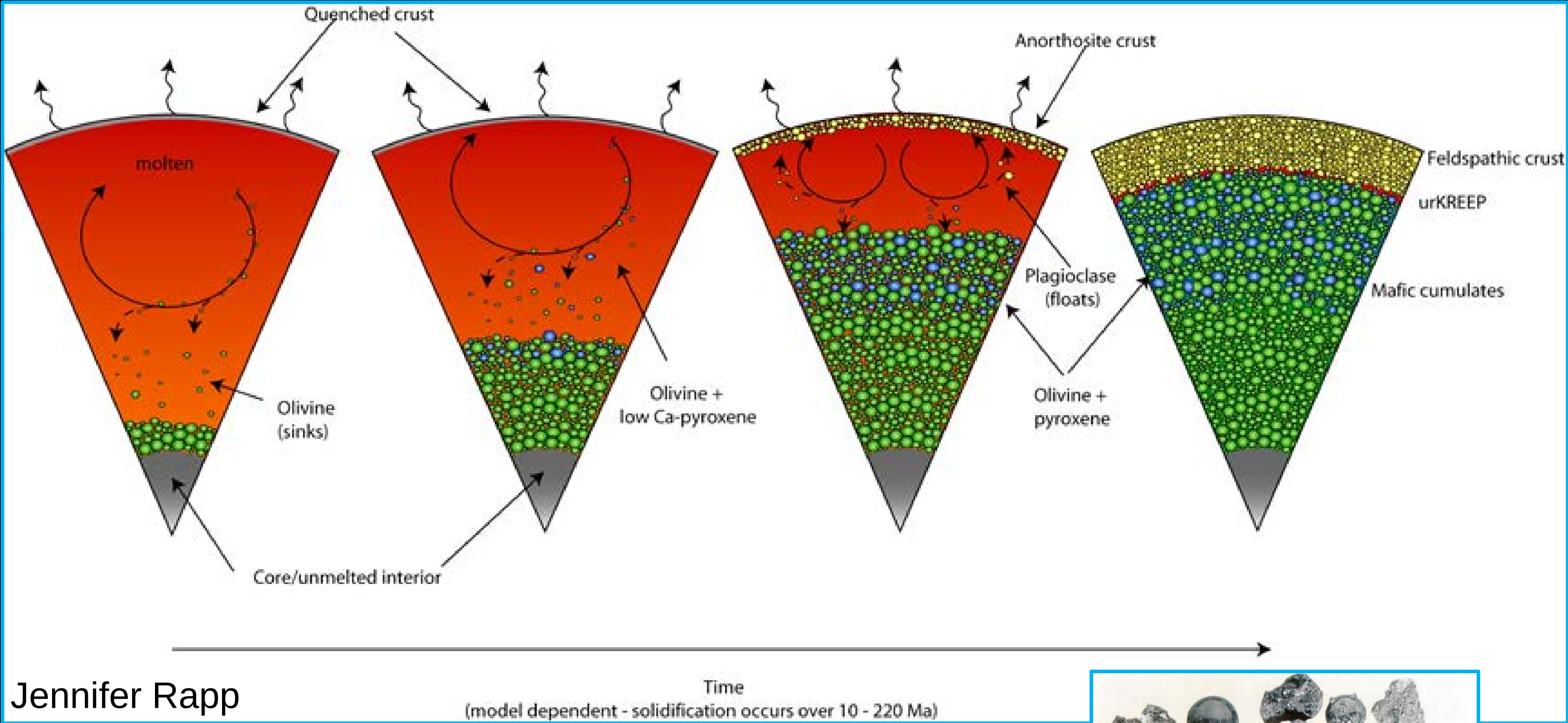
Moon-forming Impact
~50-55 Myr, although possibly as early as 30 Myr
(e.g., Halliday & Kleine, 2006
& Nemchin et al., 2009)

The Earth-Moon System



Initially the Moon was very close to Earth, ~3.8 Earth-radii. At that time, while the Moon was still molten, it would have filled a much larger fraction of the sky as seen from Earth. Over the past 4.5 billion years the Moon as moved farther from the Earth and continues to recede at a rate of ~3.8 cm/year.

Crystallization of the Lunar Magma Ocean (LMO)



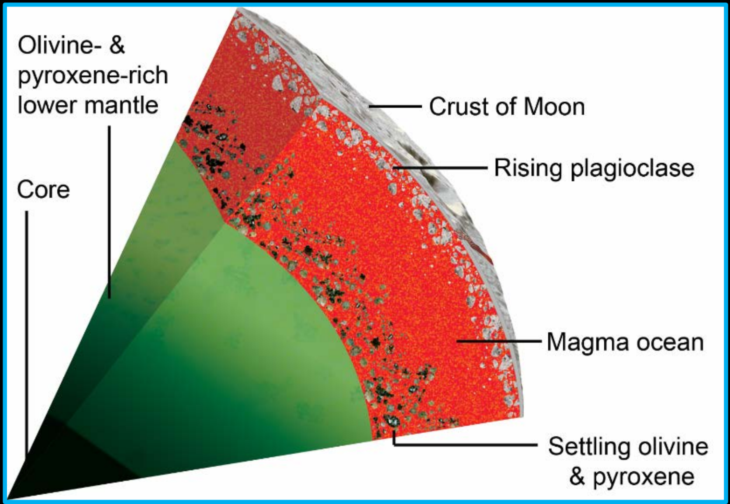
Jennifer Rapp

Demonstrating the power of sample return.

The magma ocean hypothesis emerged when Apollo 11 soil samples were analyzed and snow-white particles of anorthosite were found (Wood et al., 1970a,b; Smith et al., 1970).

John A. Wood

Timing of LMO Crystallization



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Lunar Magma Ocean Crystallization & Solidification

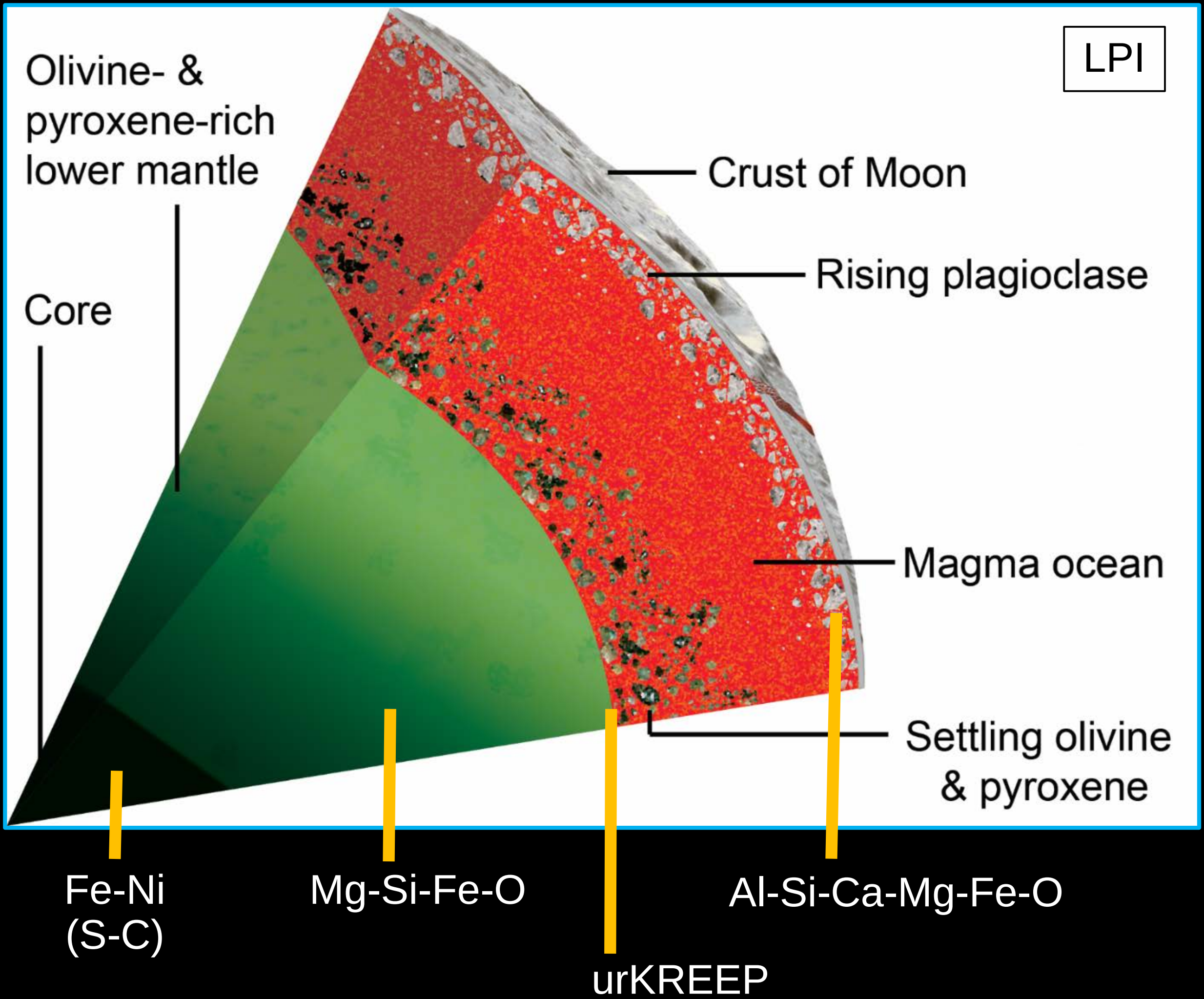
Anorthositic crust begins to form ~61 million years after lunar formation
(~106 million years from time zero)

Crystallization is complete ~39 million years later
(~145 million years from time zero)
(e.g., Nemchin et al., 2009)

0 50 100 150 200

Time (Millions of Years)

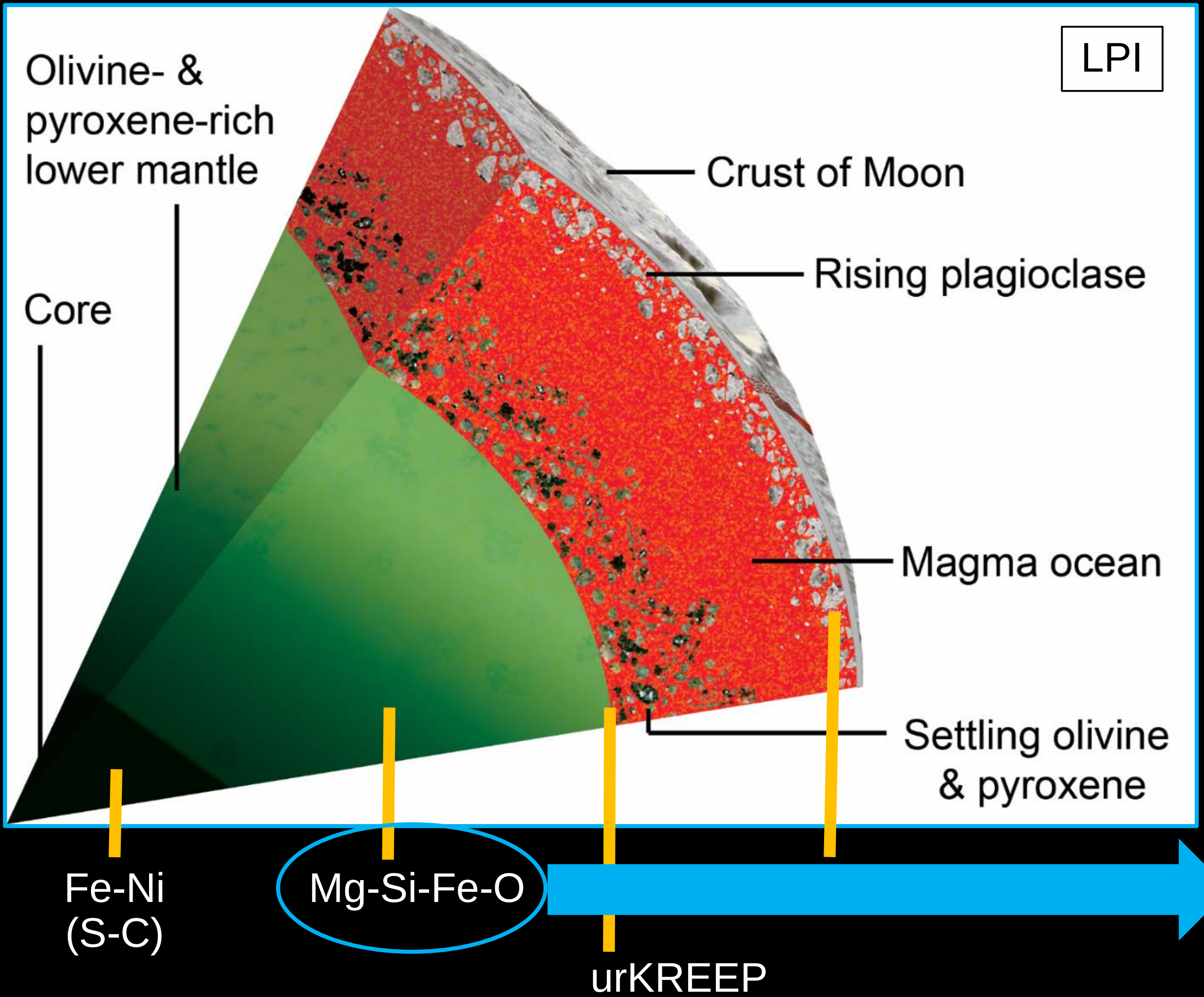
Distribution of Major Elements



Differentiation

Mineralogical differentiation that occurs during the crystallization of the lunar magma ocean also differentiates the chemistry of the Moon, producing a stratified sequence with Mg & Fe enriched at deeper levels and Al & Si enriched at the surface.

Distribution of Major Elements



Differentiation

Mineralogical differentiation that occurs during the crystallization of the lunar magma ocean also differentiates the chemistry of the Moon, producing a stratified sequence with Mg & Fe enriched at deeper levels and Al & Si enriched at the surface.

The mantle also contains Ti, which is distributed heterogeneously, affecting the distribution of ISRU-relevant ilmenite deposits on the lunar surface, as illustrated later in the lecture.

Core, Mantle, and Crust Compositions

The community still debates the major element compositions of the core, mantle, and crust. One set of compositions is selected here to demonstrate gross chemical differences generated by the crystallization of the lunar magma ocean.

	Bulk Moon TWM model (Taylor '82)	Core (Righter…'17)	LMO cumulates TWM model (Elardo…'11)	Average Crust (Korotev…'03)
Oxides (wt%)				
SiO_2	44.4	-	41.5	44.96
TiO_2	0.31	-	0.02	0.22
Al_2O_3	6.1	-	1.13	28.54
CaO	4.6	-	0.35	16.42
MgO	32.7	-	47.5	5.31
FeO	10.9	-	8.95	4.01
MnO	0.15	-	0.11	0.06
Cr_2O_3	0.61	-	0.41	0.09
P_2O_5	0.01	-	0	0.02
Na_2O	0.09	-	0	0.34
K_2O	0.01	-	0	0.03
Metals (wt%)				
Fe		90		
Ni		9		

Comparing Compositions of Earth's Crust and Moon's Crust

The Earth's crust is granitic, while the lunar crust has a major anorthositic component. For that reason, Earth's crust is enriched in SiO_2, FeO, Na_2O, and K_2O relative to the Moon's crust; the Moon's crust is, in turn, relatively enriched in Al_2O_3 and CaO.

Oxides (wt%)	Average Continental Crust of Earth (Taylor & McLennan 1985)	Average Lunar Crust (Korotev et al. 2003)
SiO_2	57.3	44.96
TiO_2	0.9	0.22
Al_2O_3	15.9	28.54
CaO	7.4	16.42
MgO	5.3	5.31
FeO	9.1	4.01
MnO	-	0.06
Cr_2O_3	-	0.09
P_2O_5	-	0.02
Na_2O	3.1	0.34
K_2O	1.1	0.03

The Mysterious urKREEP Source Region and KREEP Basalt

The prefix "ur" is old German and means "proto-" or "primitive."

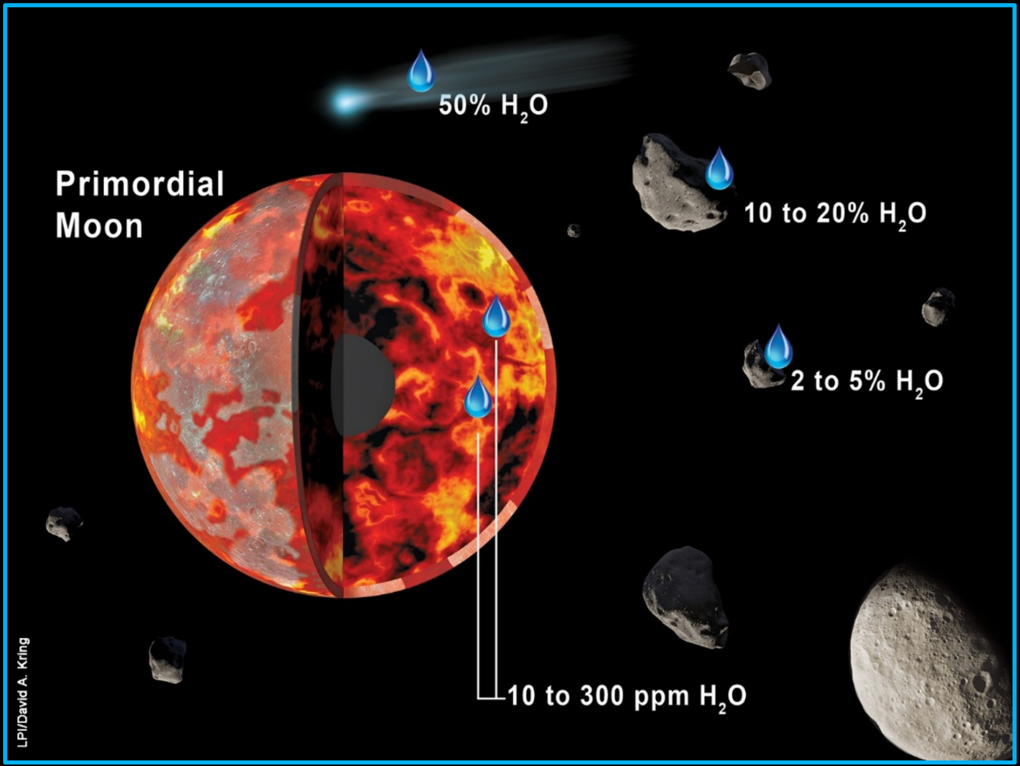
	urKREEP 15405c (Warren '88)	KREEP basalt 15382 (Dowty '76) (Hubbard '73)
Oxides (wt%)		
SiO_2	56.4	52.4
TiO_2	1.85	1.78
Al_2O_3	12.6	17.8
CaO	8.10	9.9
MgO	3.60	7.1
FeO	13.5	8.6
Cr_2O_3	0.20	-
P_2O_5	-	0.55
Na_2O	0.89	0.96
K_2O	2.06	0.57
REE (ppm)		
Sm	87.5	35.5
Eu	2.65	2.77

KREEP

Although the term KREEP denotes a lithology rich in K, REE, and P, the abundances of REE are still not very high. Summed REE values in urKREEP and KREEP-rich mare basalts are 10 to 1000 ppm.

In contrast, hard rock ore mined in China has 40,000 to 100,000 ppm REE (Kramer, 2018). Other terrestrial sources of REE are coal (~60 ppm) and fly ash (~400 ppm).

Sources of Water in the Lunar Interior



Sources

Based on H- and N-isotope data, the delivery of volatiles was dominated by water-rich carbonaceous chondrite asteroids, similar to a mixture of CO-, CI-, CM- and possibly CV-type CCs.

A minor contribution of water from deuterium-rich Oort cloud or Kuiper belt comets is possible, but did not exceed 20% of the total water in the Moon.

Saal et al. (Science, 2013); Füri et al. (Icarus, 2014); Barnes et al. (Nature Communications, 2016).

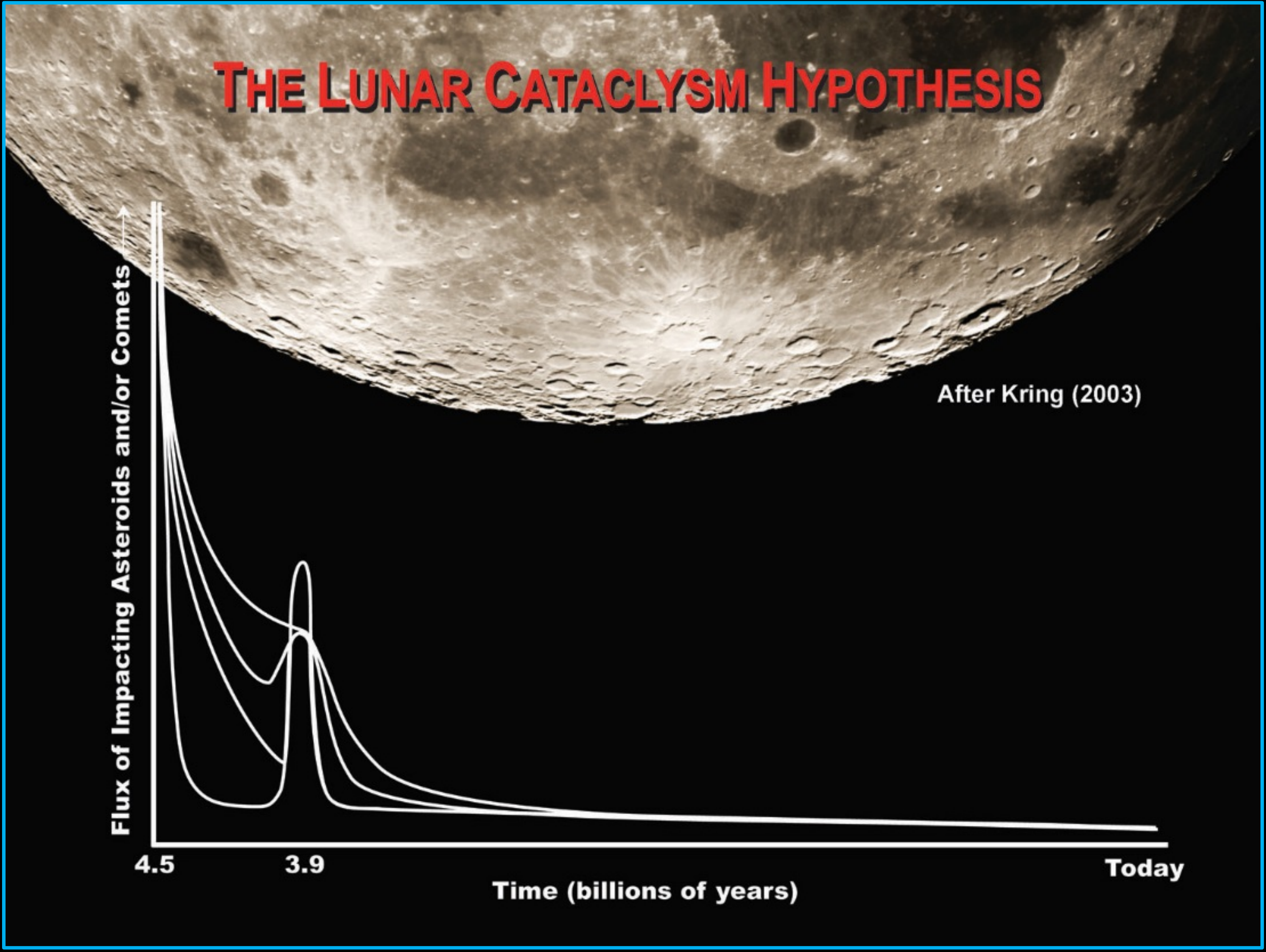
Sizes of Water Reservoirs

Lunar Water Reservoirs

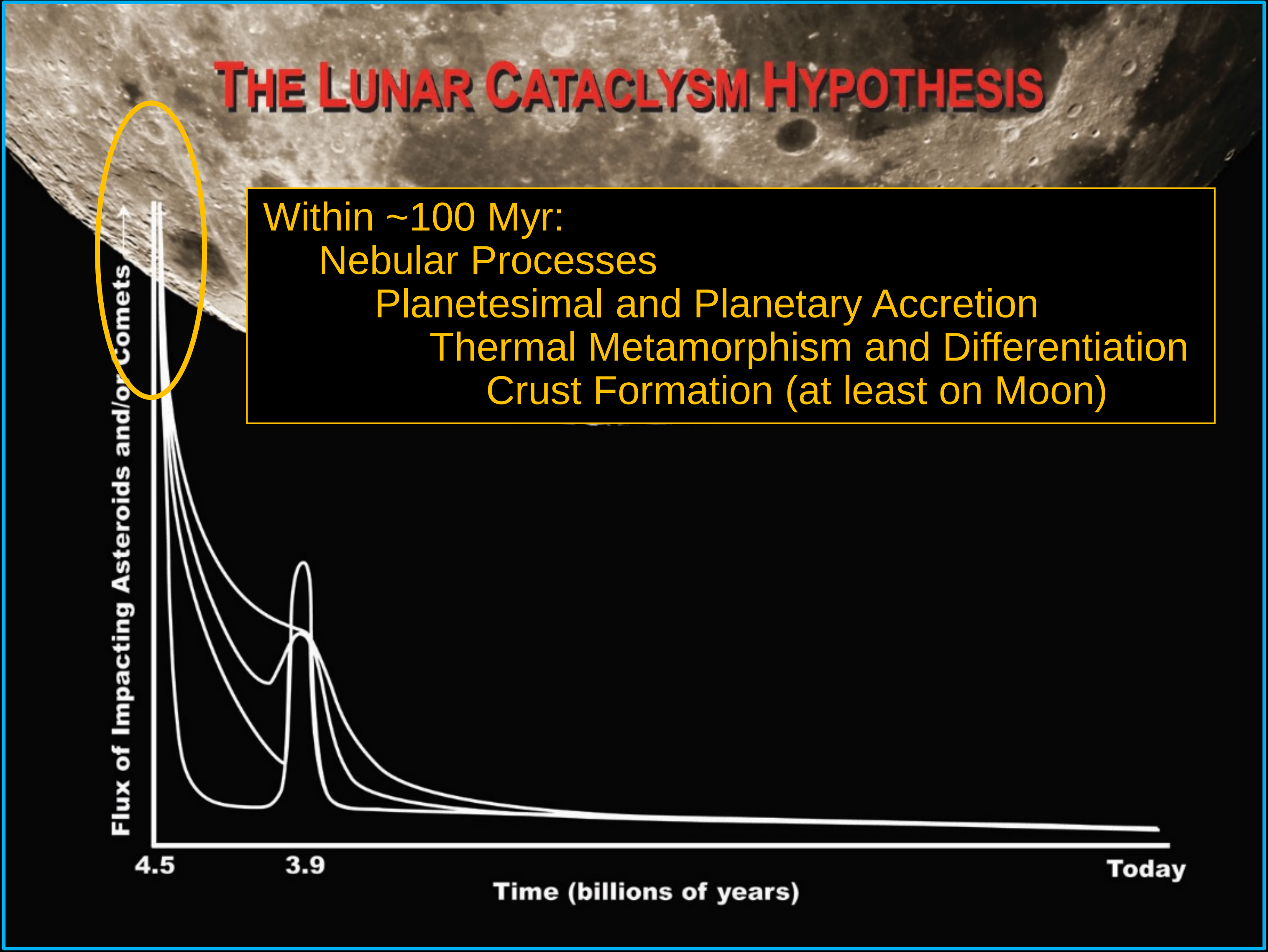
"Integrated total inventory of H poleward of 80° latitude is 10^{11} kg" (Hurley et al., 2016) or 10^{12} kg H_2O at the lunar surface. That mass is equivalent to water filling ~3.6 million Olympic-sized swimming pools of water.

The amount of water in the lunar interior is many orders of magnitude larger, although it is not as accessible or useful for space exploration (except where and when it was vented volcanically). The amount of water in the lunar interior is equivalent to 4 billion to 4 trillion Olympic-size swimming pools of water.

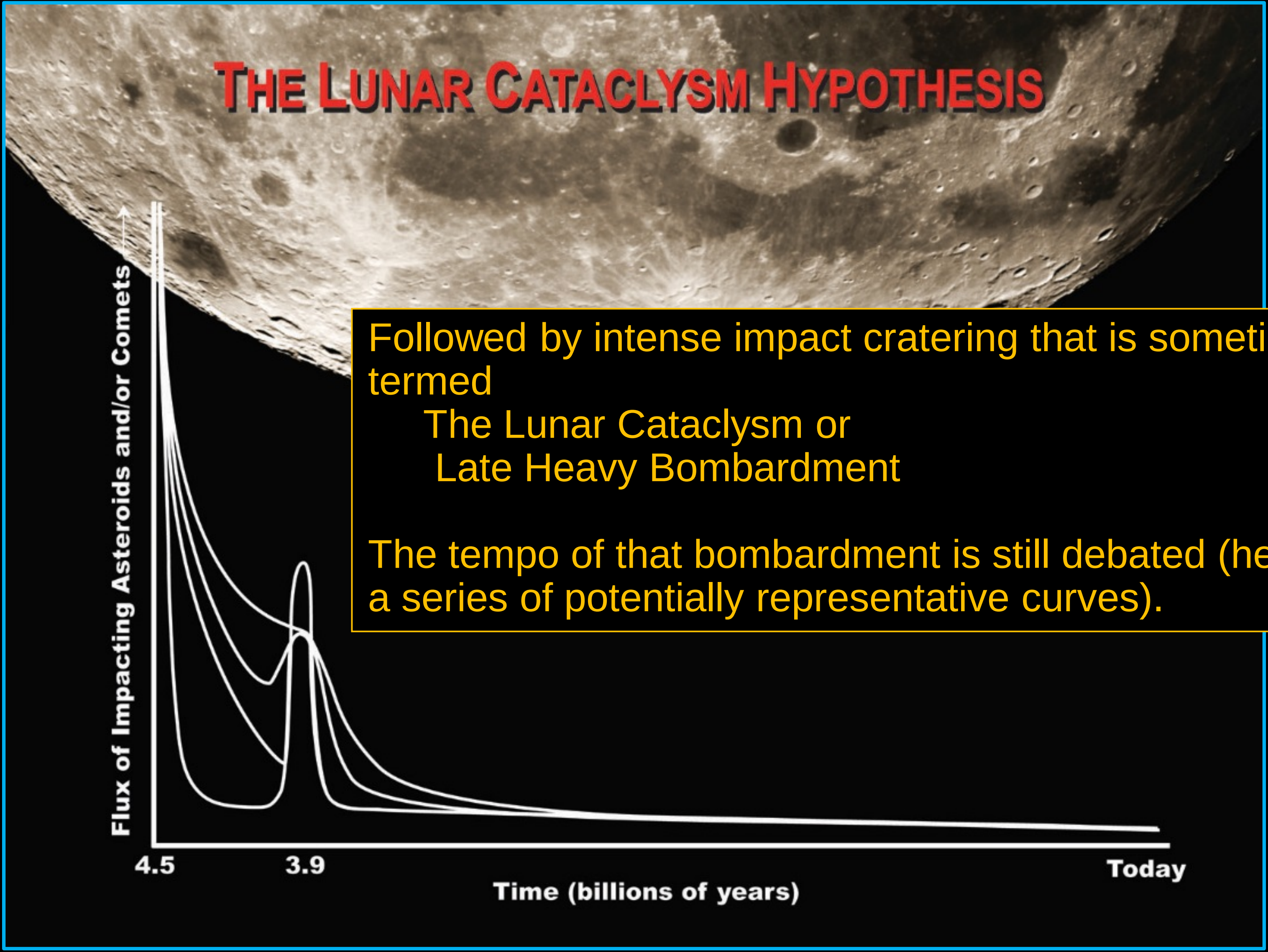
Impact Bombardment of the Lunar Surface



Impact Bombardment of the Lunar Surface



Impact Bombardment of the Lunar Surface



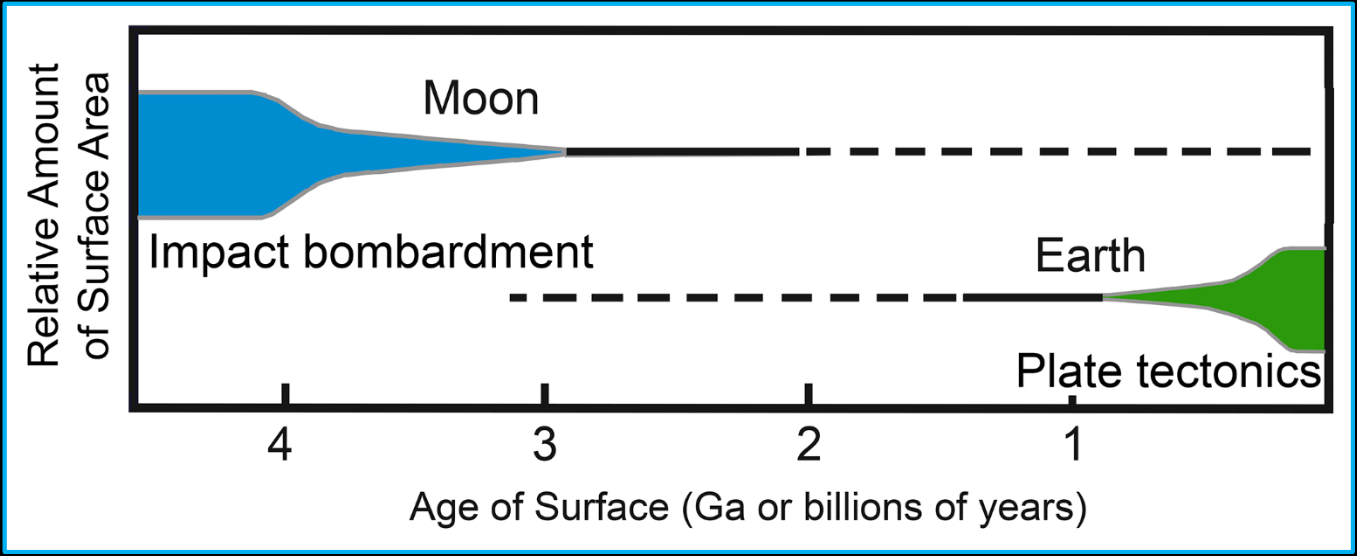
Followed by intense impact cratering that is sometimes termed

The Lunar Cataclysm or

Late Heavy Bombardment

The tempo of that bombardment is still debated (hence a series of potentially representative curves).

Disparate Geological Evolution Produces Different Geological Surfaces



Data from James W. Head

Consolidated Lunar Atlas H12

Detail from Blue Marble 201408

GSFC SVS

The Intensely Cratered Surface Affects Lunar ISRU Potential

Important

1. The topography of impact craters in the polar regions produces the permanently shadowed regions (PSRs) where volatiles can be trapped.
2. Impacting asteroids (and, to a lesser degree, comets) were a source of the volatiles that could be trapped in those PSRs.
3. The largest impact events altered the spin axis of the Moon and, thus, the locations of PSRs where volatiles could accumulate.
4. The largest impact basins thinned the crust, allowing large volumes of magma to reach the surface and vent volatiles, providing another source of volatiles that could be trapped in PSRs.
5. Impact ejecta from cratering events covered (and potentially reworked via ballistic sedimentation) horizons of ice deposited in PSRs, producing a stratigraphic succession.
6. Those same impact basins provided catchments for flood basalts (mare) that contain ilmenite that can be chemically modified to produce oxygen.

The Intensely Cratered Surface Affects Lunar ISRU Potential

Important

7. Ongoing impacts, including micrometeoritic impacts, have infused the regolith with meteoritic-derived volatile abundances. Those volatiles, when combined with volatiles from the solar wind, provide a recoverable reservoir everywhere on the Moon. They have also infused the soil with meteoritic metal, which is another potential resource for a sustainable exploration program.
8. The largest of those impacts produced melt sheets that may have differentiated, potentially forming ore deposits of metal and sulfide.

Impact cratering is the single most important geologic process affecting ISRU prospects.

Let's step through each of those eight examples in more detail.

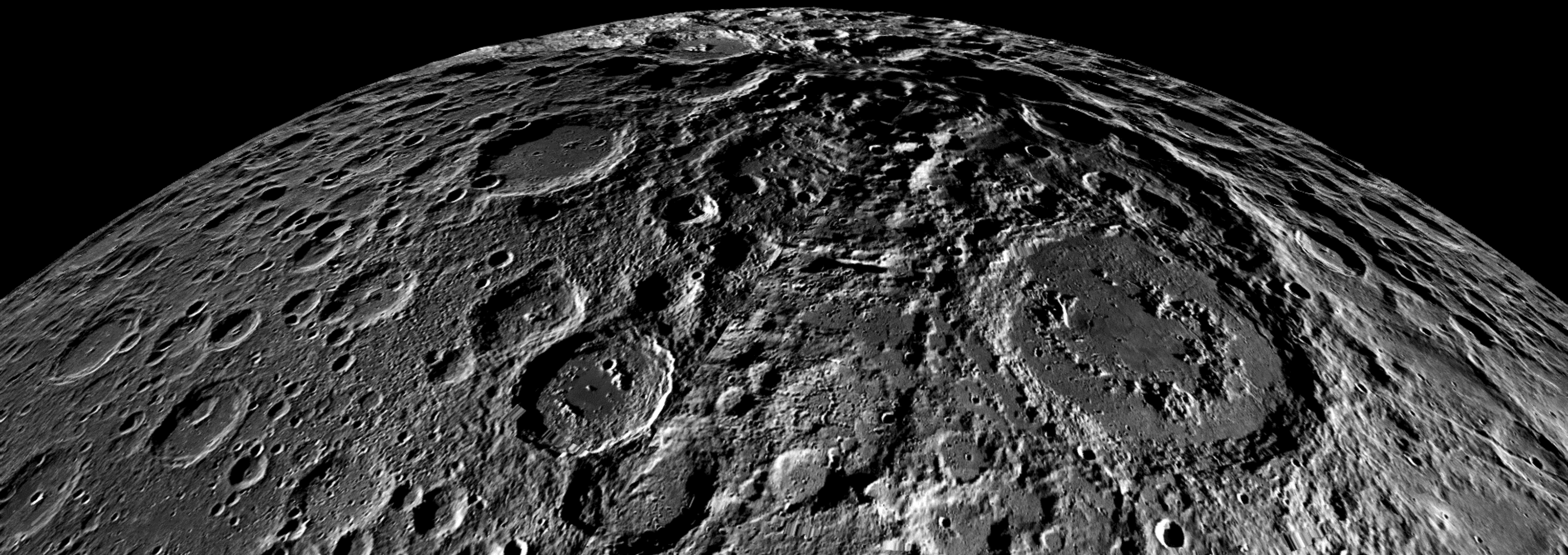
1

Topography produced by impact craters in the polar regions produces the permanently shadowed regions (PSRs) where volatiles can be trapped.

Impact Bombardment of the Lunar Surface – Creating PSR Traps

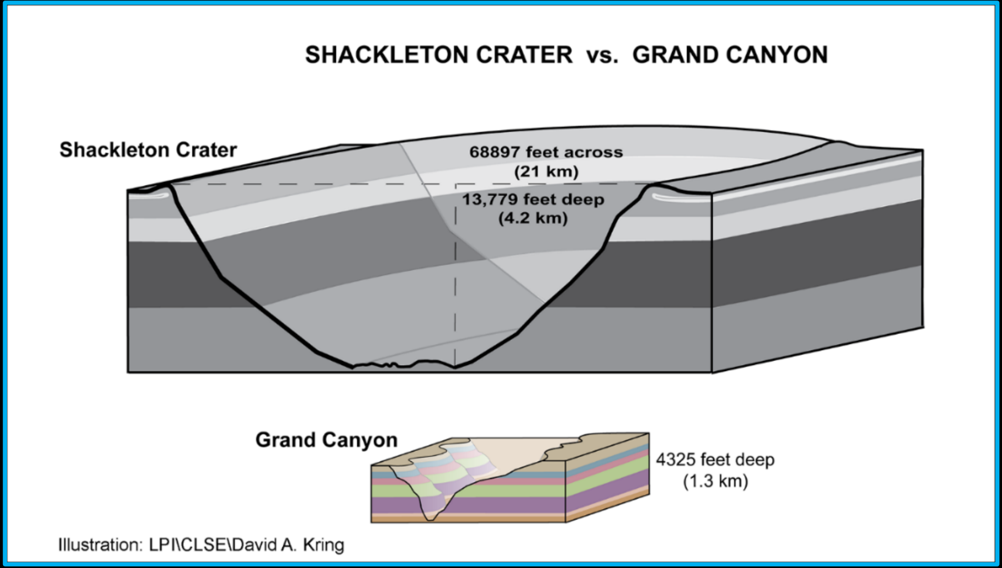
That bombardment produced the dramatic topography at the poles that harbor permanently shadowed regions (PSRs). Without impact craters, the sites being targeted by astronauts and robotic spacecraft for water ice and other volatiles would not exist.

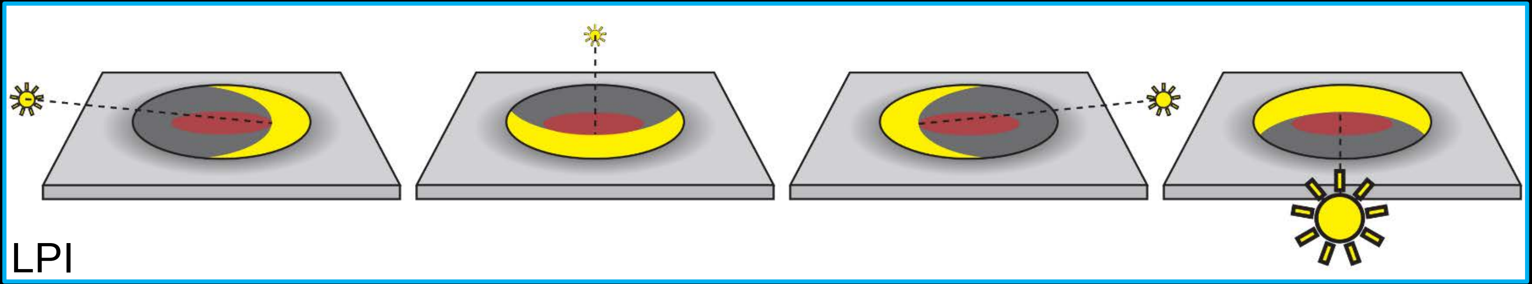
The impact-cratered terrain of the lunar south pole.



Impact Bombardment of the Lunar Surface – Creating PSR Traps

For example, the south pole's Shackleton crater is over 4 km deep, which is >3 times deeper than the Grand Canyon. With the sun perpetually near the horizon at the lunar poles, a topographic depression of that size is ensured permanent shadow.

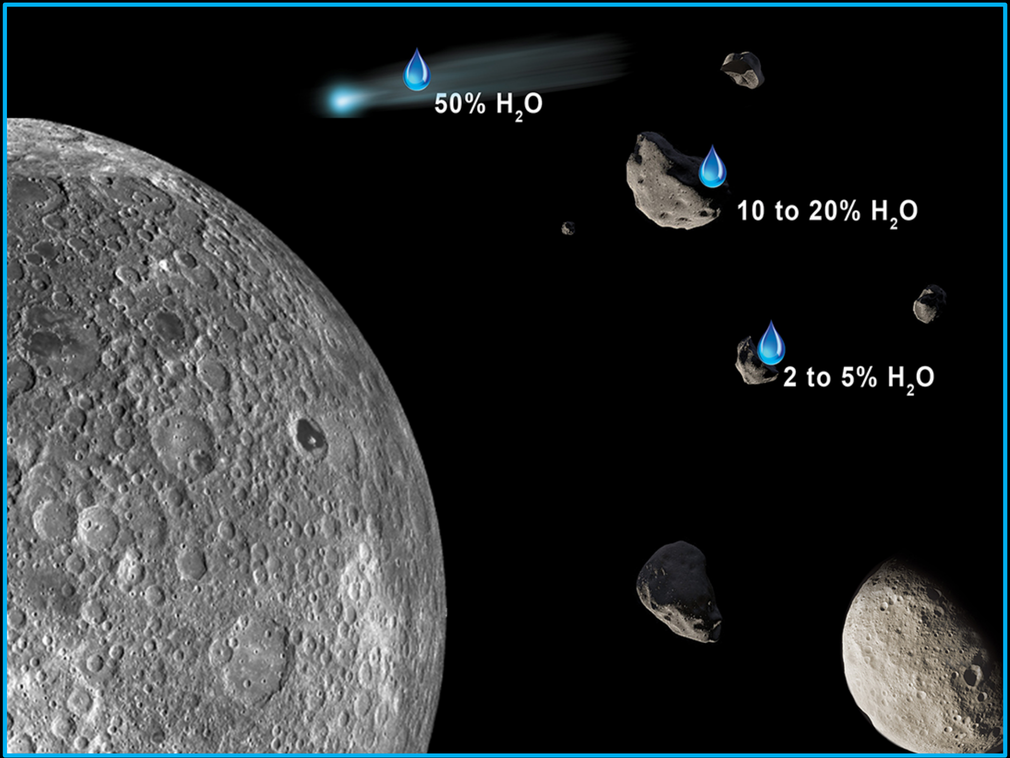




2

Impacting asteroids (and, to a lesser degree, comets) were a source of the volatiles that could be trapped in those PSRs.

Impact Bombardment of the Lunar Surface – Delivering Volatiles



David A. Kring

Impacting asteroids and comets continued to deliver volatiles to the lunar surface.

Mineralogic, geochemical, isotopic, and geologic evidence suggests most impactors were asteroids.

Although asteroids are often thought of as dry rocky bodies, they can contain up to 20 wt% H_2O.

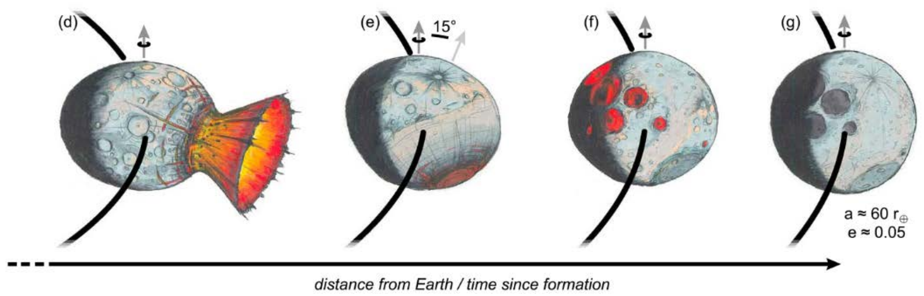
Some of the volatiles may be ejected with escape velocities during impact, but a significant fraction will be retained by the Moon.

3

The largest impact events altered the spin axis of the Moon and, thus, the locations of PSRs where volatiles could accumulate.

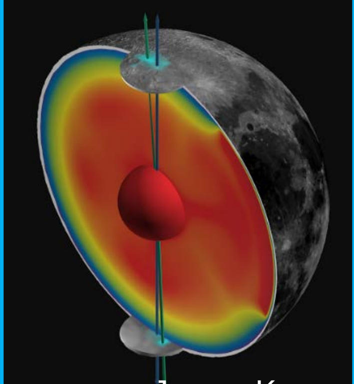
Impact Cratering and Volcanism May Shift Pole Locations

Impacts during the period of basin formation may have caused the pole positions to shift and, thus, cause the locations of PSR traps for volatiles to shift. Likewise, an intense period of magmatism on the nearside may have caused a polar shift, too.



Keane & Matsuyama (GRL 2015)

The SPA impact in this model caused a 15° shift, moving SPA closer to the south pole (Keane & Matsuyama, GRL 2015).



James Keane

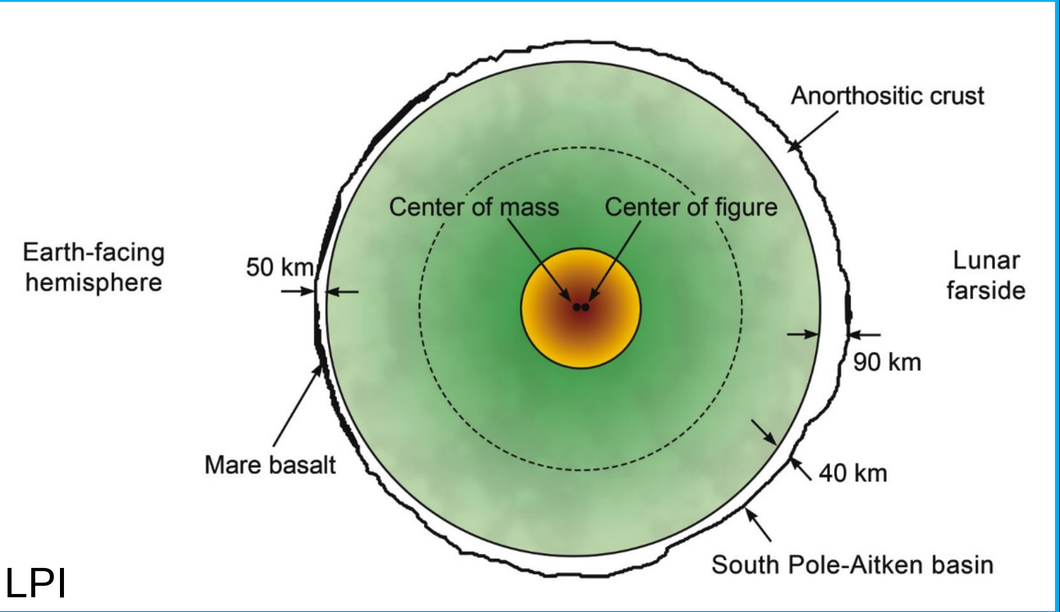
Procellarum magmatism may have caused 8° of polar wander, expanding the polar area over which H could be trapped (Siegler et al., Nature 2016).

Per the Lunar Magmatism Hypothesis (Kring, 2015), the SPA impact event may have triggered the nearside magmatic event circa 4.36 Ga.

4

The largest impact basins thinned the crust, allowing large volumes of magma to reach the surface and vent volatiles, providing another source of volatiles that could be trapped in PSRs.

The Thickness of the Lunar Crust



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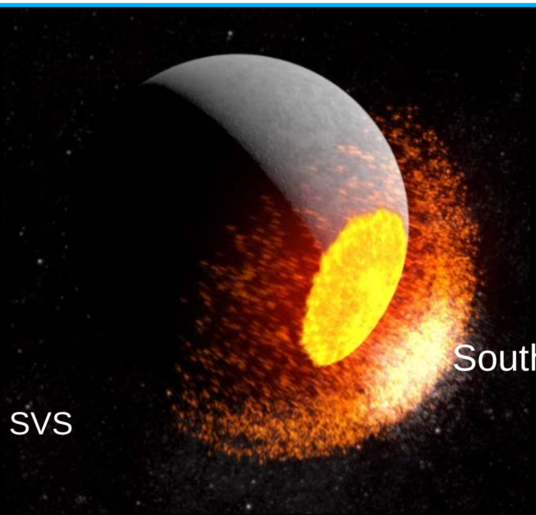


GSFC SVS

South Pole-Aitken (SPA) impact

Crustal Dichotomy

The crust in the mid- to northern latitudes on the farside of the Moon is much thicker than on the nearside of the Moon.

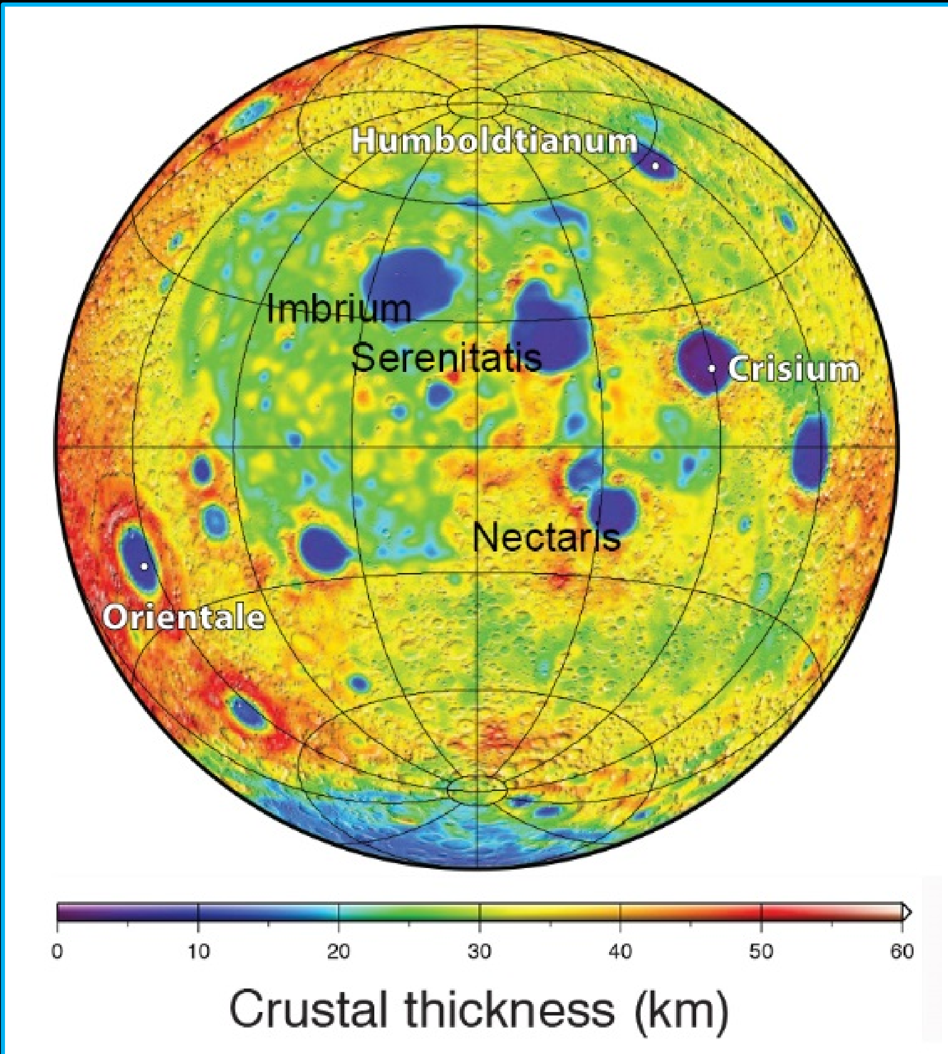
The crust in the southern latitudes of the farside is thin, because rock was excavated by the South Pole-Aitken impact event.

Only a small amount of mare (basaltic plain) lavas rose through the crust on the farside to erupt at the surface.

Most mare lavas on the Moon fill impact basins on the nearside.

The distribution of mare affects ISRU plans that rely on basalt as its feedstock.

The Thickness of the Lunar Crust

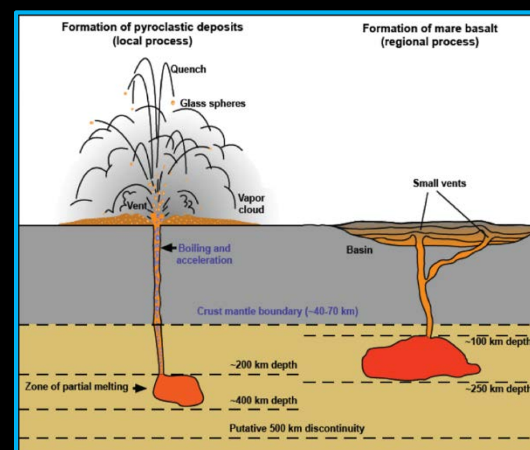


Wieczorek et al. (2013)

Basin-size impacts excavated large amounts of crust, leaving behind very thin crust.

The Imbrium, Serenitatis, Nectaris, and Crisium basins have crust less than 20 km thick.

Magmas rising from the mantle have less crust to penetrate and, thus, are more likely to reach the surface.



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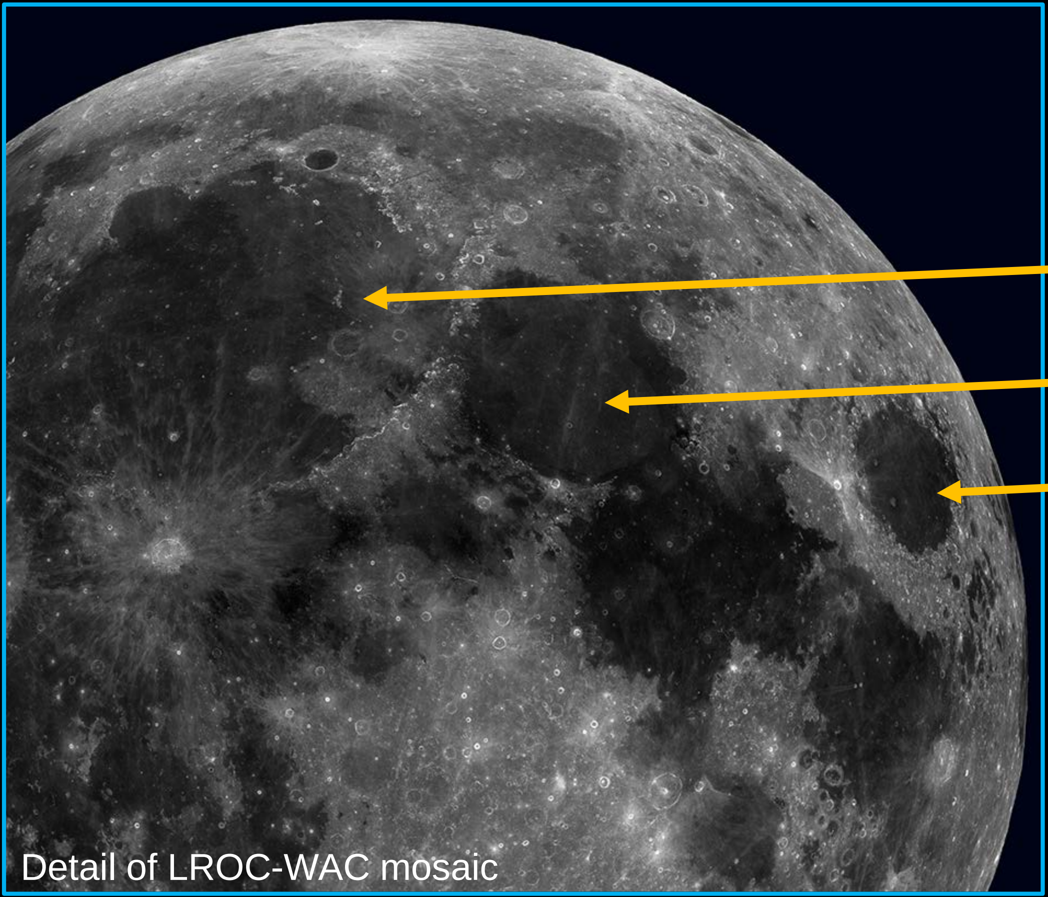
Impact Bombardment of the Lunar Surface – Creating Topographic Lows to be flooded with Volcanic Lavas

Bombardment produced multi-kilometer-deep depressions in the crust that became catchments for lavas erupting onto the surface.


Detail of LROC-WAC mosaic

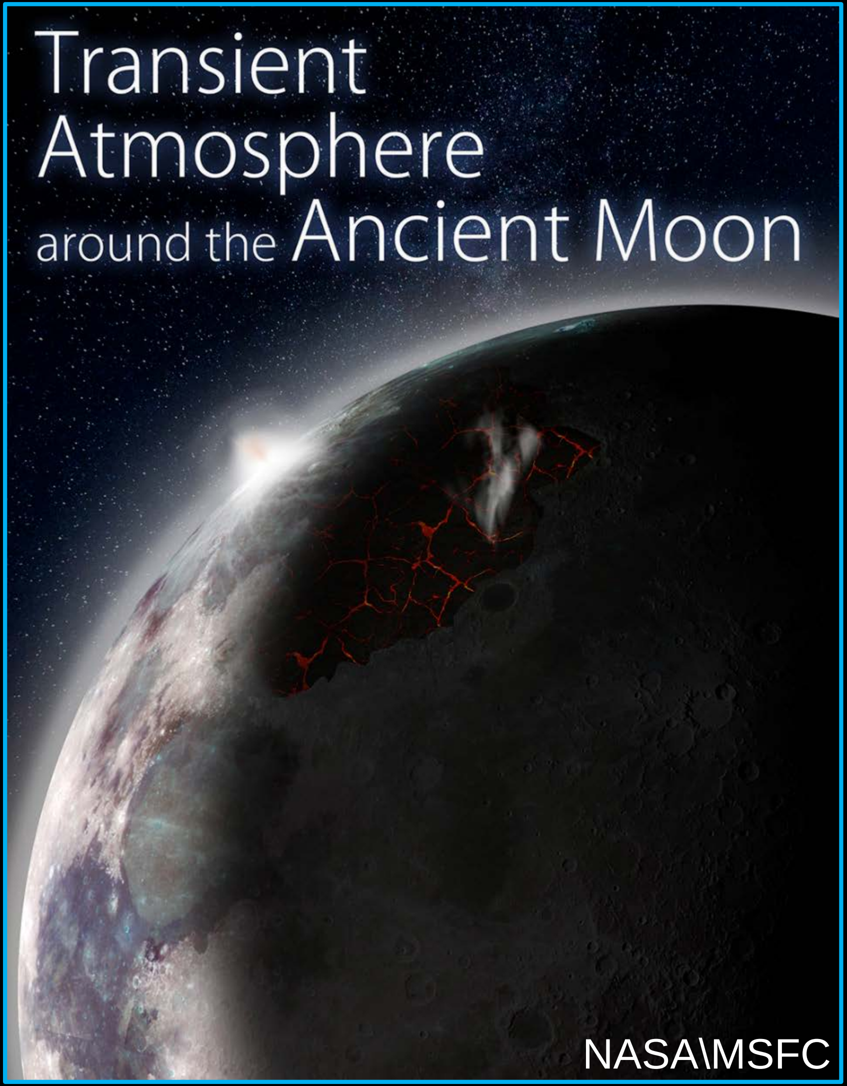
Flood basalts fill the

Imbrium impact basin,

Serenitatis impact basin, and

Crisium impact basin.

The Thickness of the Lunar Crust



Erupting lavas vented volatile molecules.

During the most intense periods of volcanism, the production rate of volatiles exceeded the escape rate to space.

At those times, a transient atmosphere may have formed around the Moon (Needham & Kring, 2017), a portion of which may have been trapped in polar PSRs.

A volcanic source of volatiles is consistent with H_2S detected in Cabeus crater ices by the LCROSS experiment.

5

Impact ejecta from cratering events covered (and potentially reworked via ballistic sedimentation) horizons of ice deposited in PSRs, producing a stratigraphic succession.

Potential ISRU Role for Volatile Elements

LPI/David A. Kring

Utility

Water, e.g.,

- Crew consumables (e.g., water, oxygen)
- Radiation shielding (water jacket)
- Rocket propellant (the fuel LH2 and the oxidizer LOX)

Volatile Sources that feed PSR Traps

LPI/David A. Kring

Volatile sources

Delivered to surface by impacting asteroids & comets (throughout lunar history, but particularly during the basin-forming epoch >3.7 Ga).

Vented volcanically from the lunar interior (e.g., at 4.3, 3.8, & 3.5 Ga).

Escaping the crustal rocks via moonquakes and impact events (throughout lunar history).

Delivered by impacting solar wind (throughout lunar history).

Deposition of Ices in Permanently Shadowed Regions

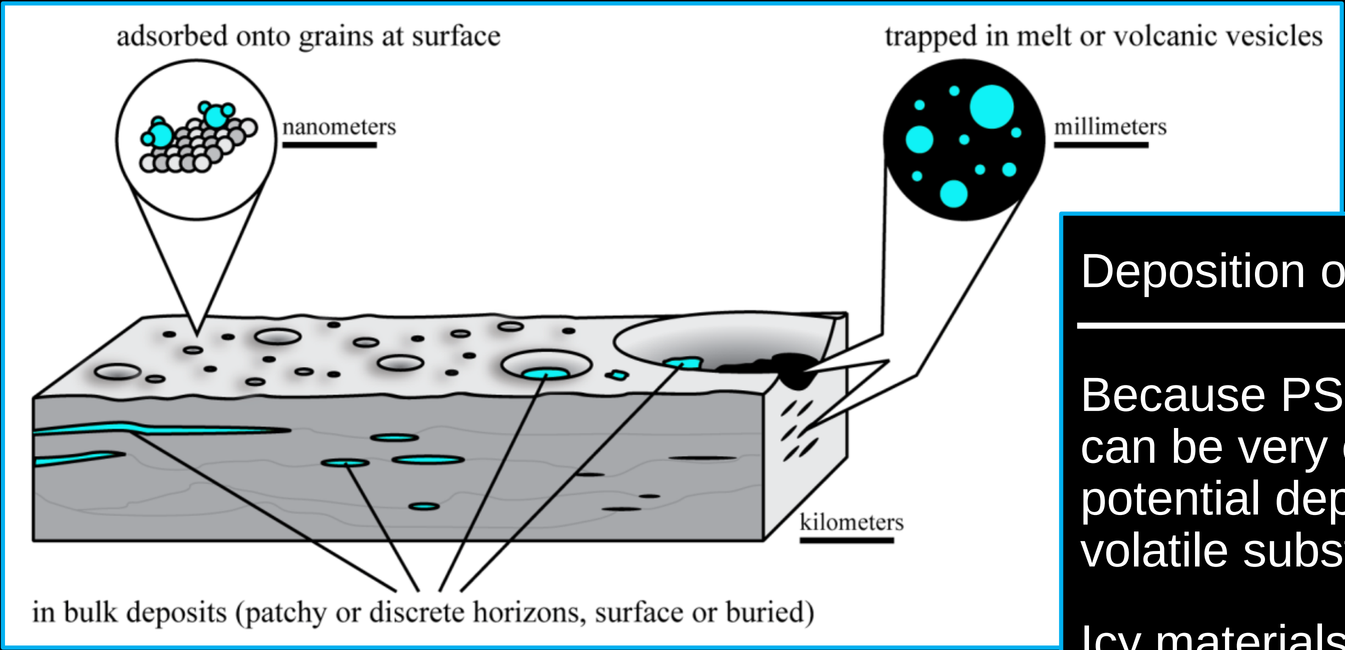


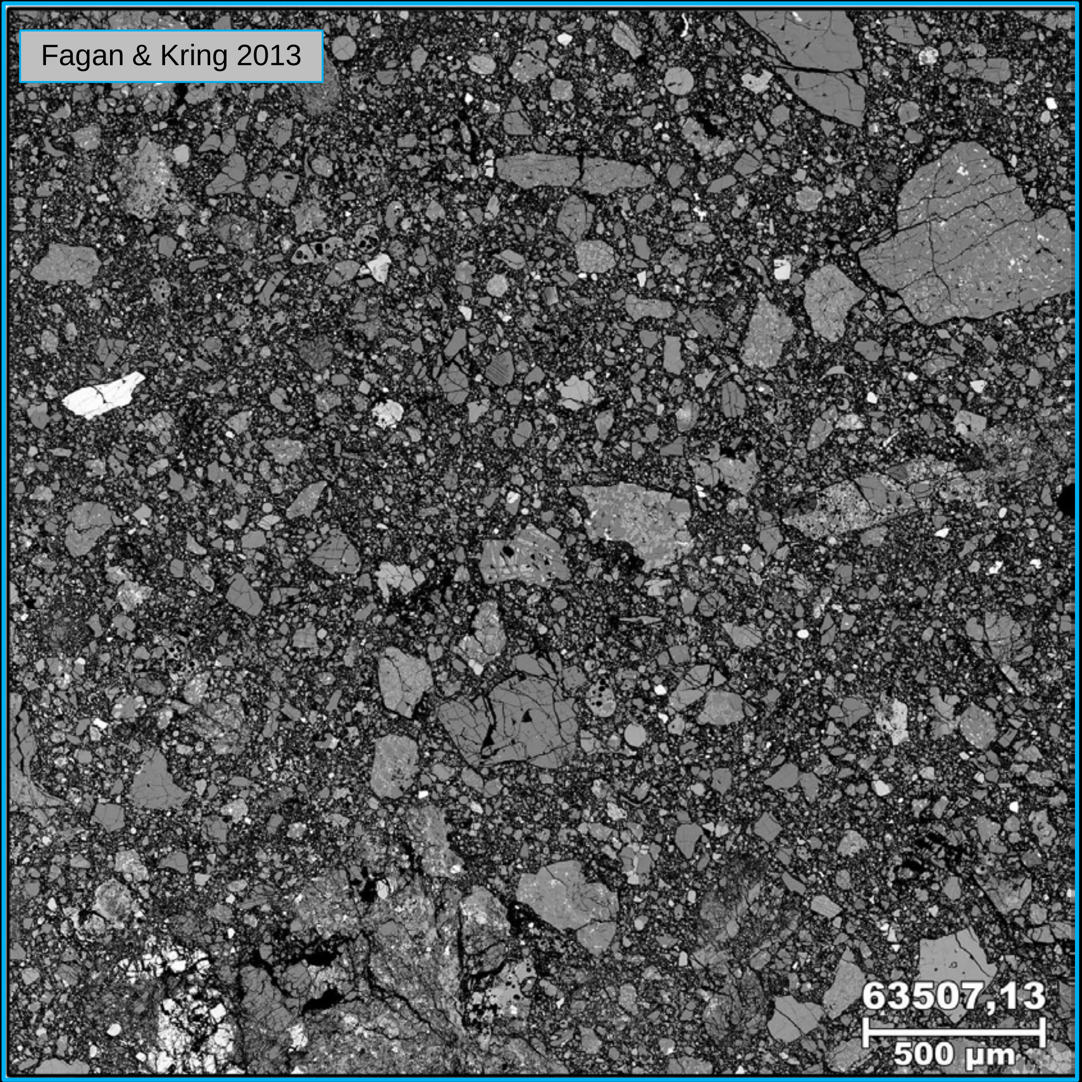
Illustration credit: LPI

Deposition of Ice

Because PSRs lack sunlight and can be very cold, they are potential depositional sites for volatile substances like water ice.

Icy materials can be deposited in the regolith in several (as yet untested) forms, as illustrated on the left.

Hypothetical Deposition of Ice



Highland regolith breccia

Sample 63507 is representative of highland regolith breccias

Feldspathic

Submature

Friable

Estimated porosity: 30%

Estimated bulk density: 2 g/cm^3

Field of view = 3 mm

Hypothetical Deposition of Ice

Water in regolith

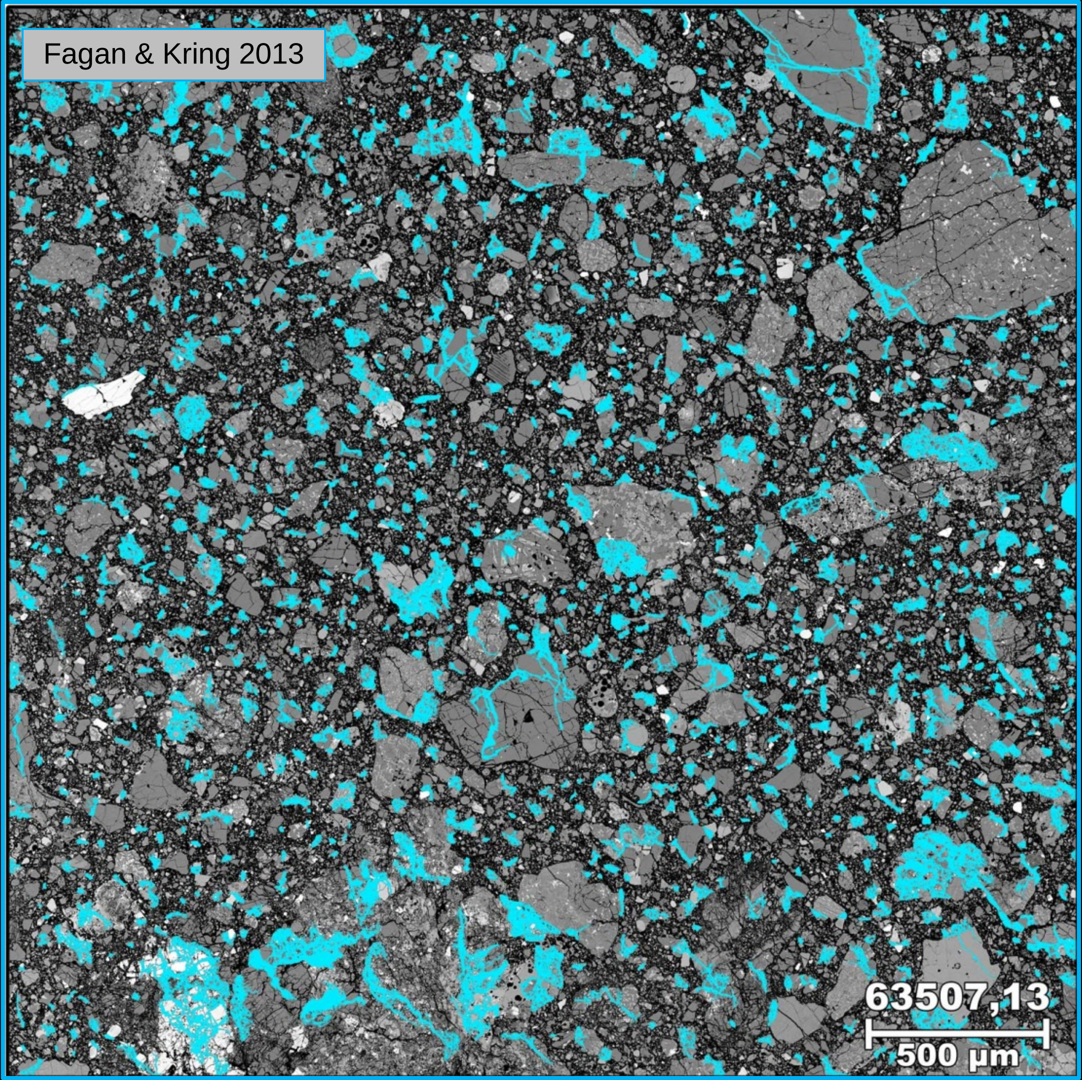
Estimates for mass of water in the regolith hit by the LCROSS impactor are ~5 wt% (e.g., Colaprete et al., 2010)

This is ~10 vol% of a highland regolith breccia, because of the density contrast between water and the rocky breccia.

If the water ice was distributed along grain boundaries, it would look like the image to the left.

Field of view = 3 mm

Hypothetical Deposition of Ice



Water in regolith

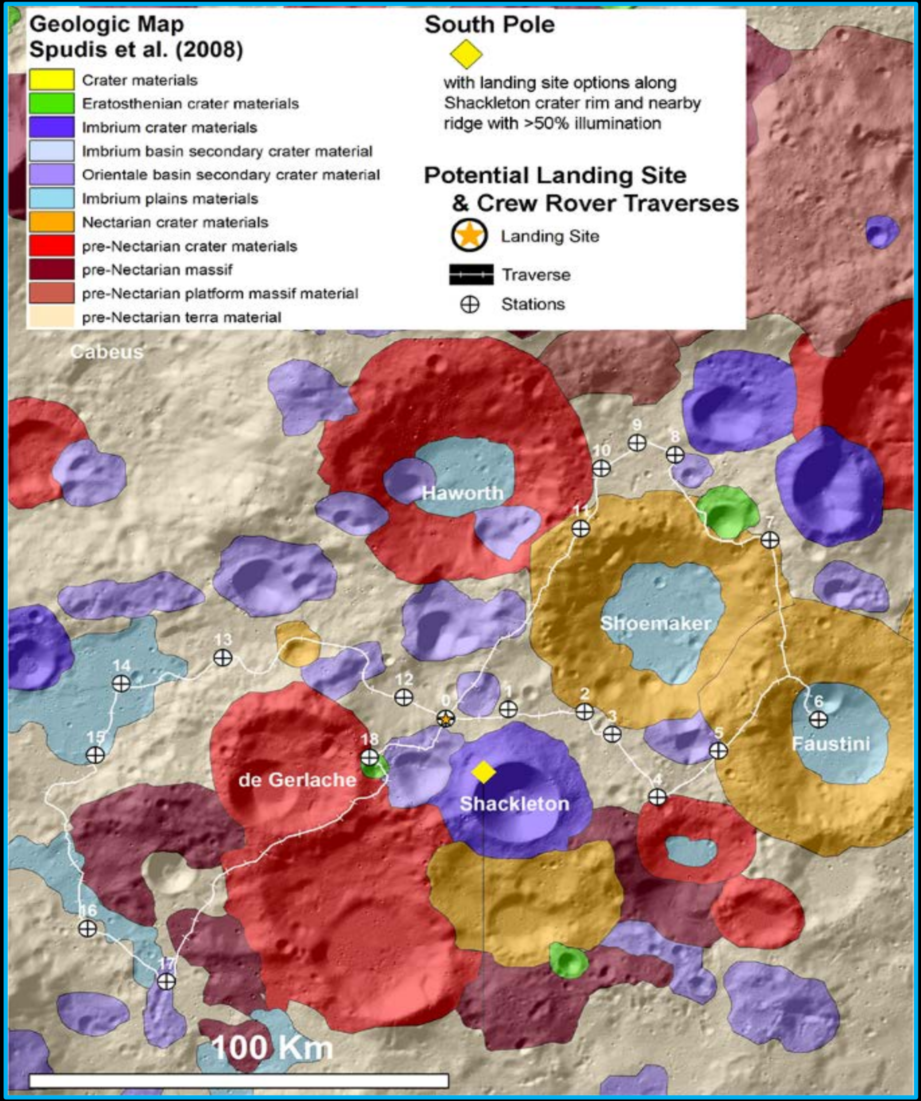
If that water ice, instead, filled large pore spaces in the regolith, it could look like the image to the left.

In either case, the result is a lower porosity and better cemented material.

Thus, the addition of water ice in a regolith breccia would seem to enhance cohesion and bearing capacity, properties that would enhance trafficabiilty

Field of view = 3 mm

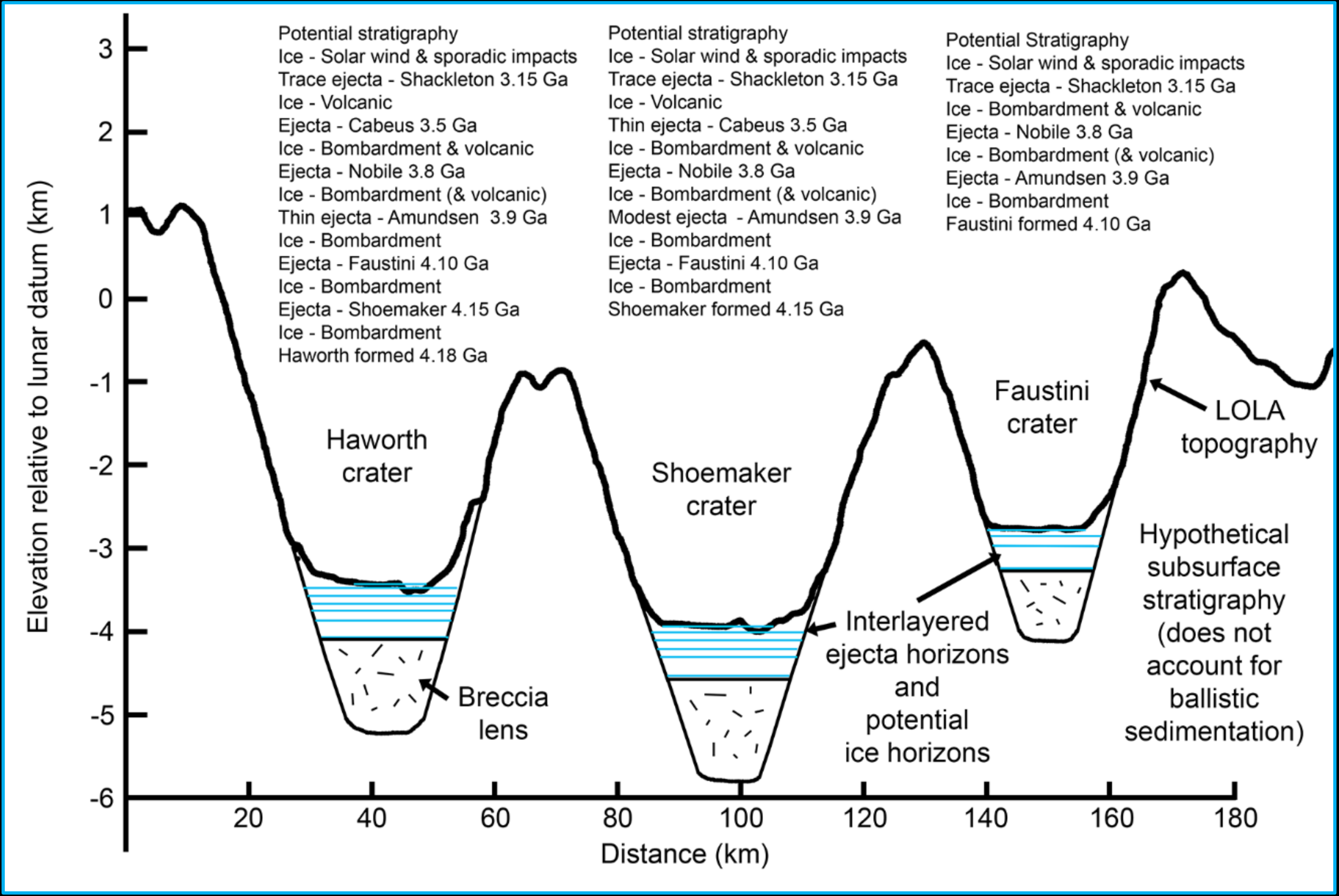
Geology of the South Polar Region



After Spudis et al. (2008) and Allender et al. (2019)

- The south polar region is a heavily cratered highland region.
- It was shaped by bombardment during the first billion years and by subsequent impact events.
- It sits on the margin of the oldest basin, the South Pole-Aitken basin.
- It was affected by ejecta from the final two basin-forming impacts: Orientale and Schrödinger.
- De Gerlache and Haworth are among the oldest craters; Shoemaker and Faustini may be younger.
- Shackleton was produced after the basin-forming epoch.

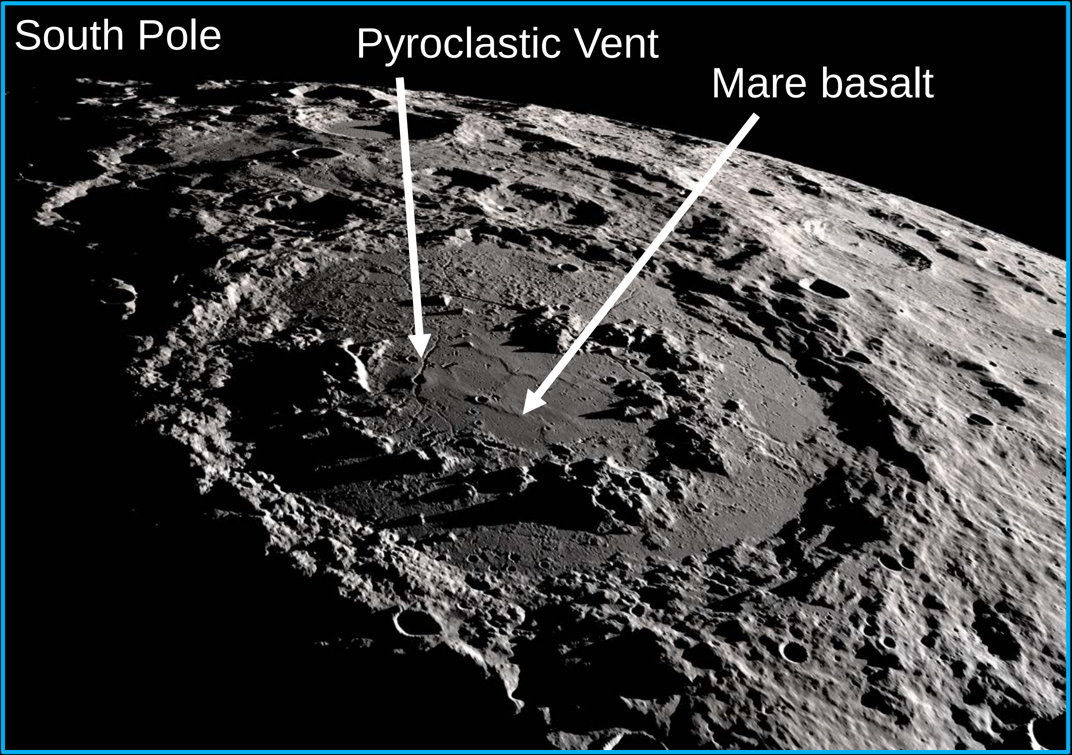
Hypothetical Stratigraphic Deposition of Ice



6

Large impact basins provided catchments for flood basalts (mare) that contain ilmenite that can be chemically modified to produce oxygen.

Mare Basalt Localities, Including Detections of Cryptomare

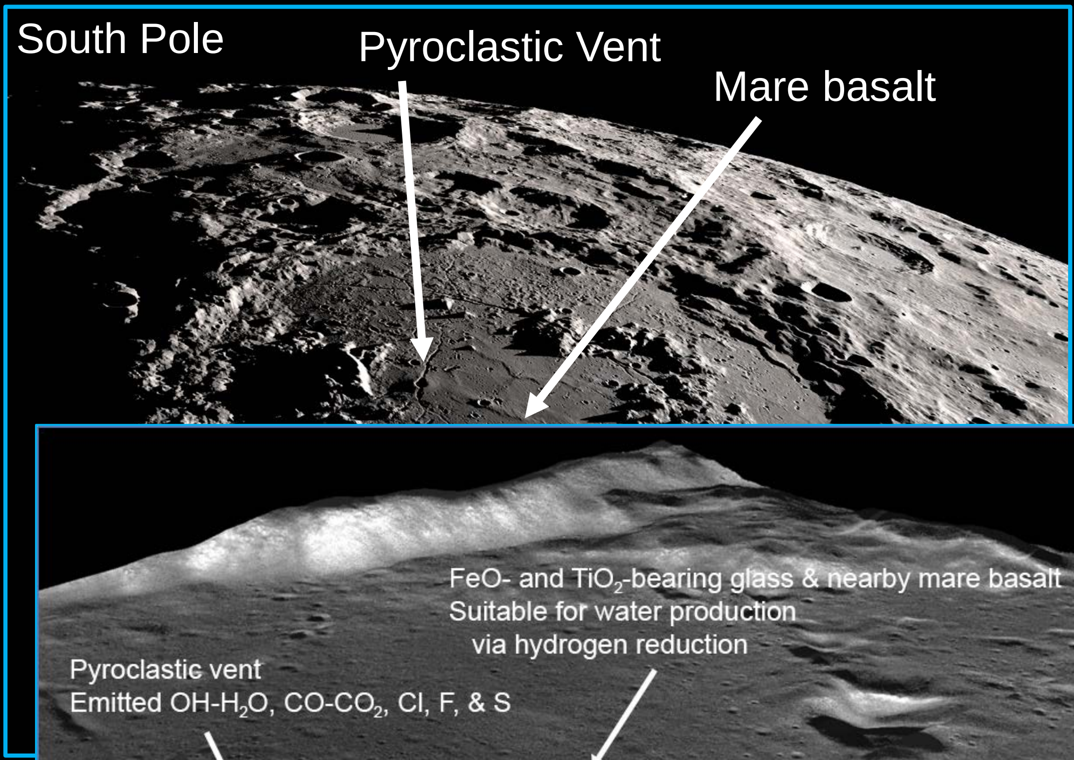


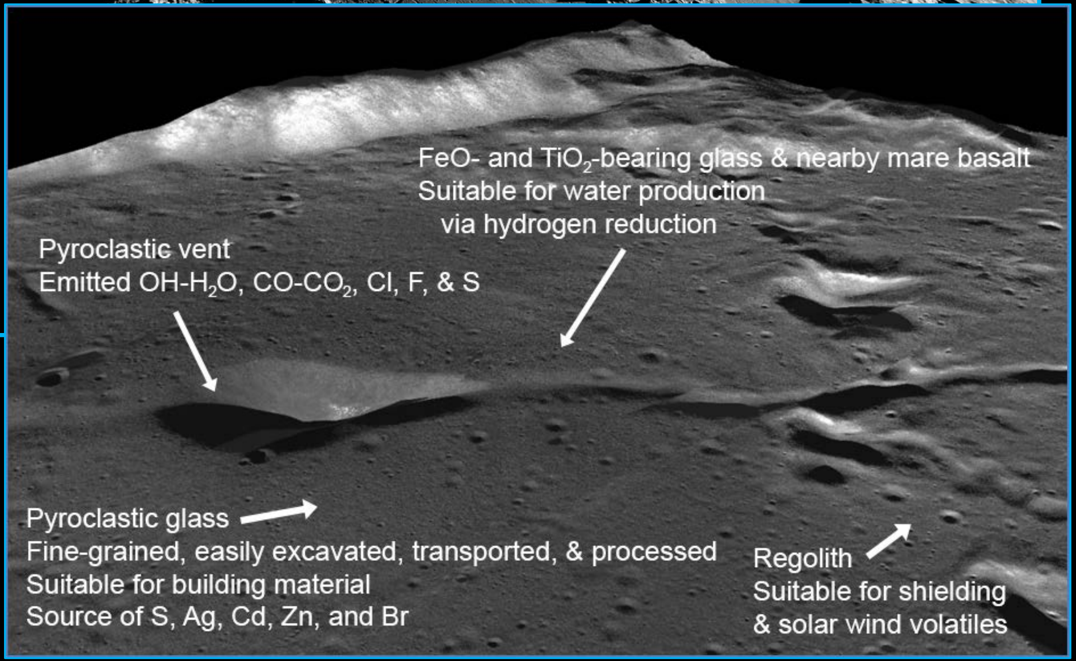
Artemis at the south pole

Because Artemis is targeting the south pole first, it is important to note that no mare basalt occurs in the immediate vicinity of the south pole.

The closest mare basalt is ~450 km from the pole on the floor of the Schrödinger basin.

Mare Basalt Localities, Including Detections of Cryptomare





Artemis at the south pole

Because Artemis is targeting the south pole first, it is important to note that no mare basalt occurs in the immediate vicinity of the south pole.

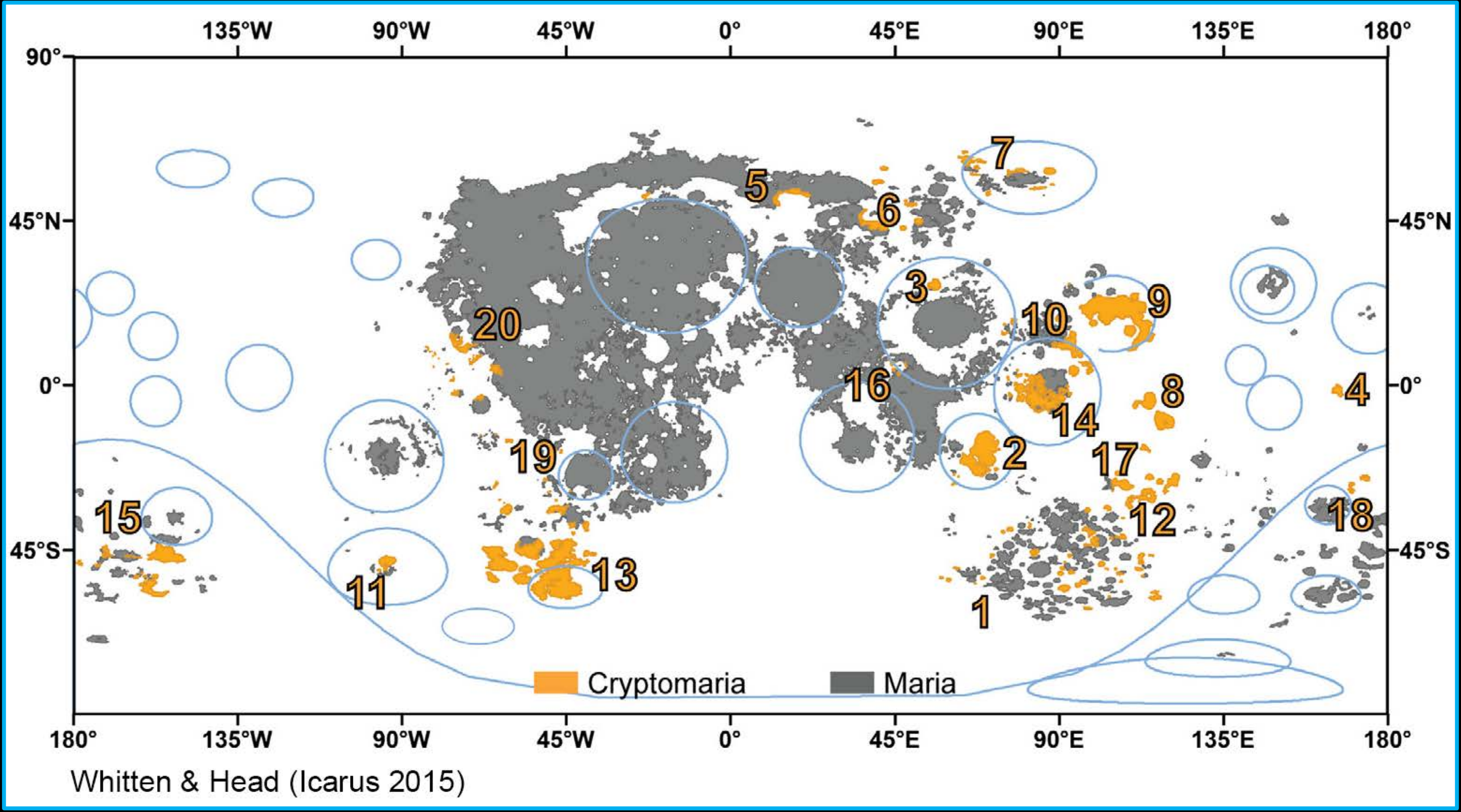
The closest mare basalt is ~450 km from the pole on the floor of the Schrödinger basin.

Schrödinger basin was an ISRU top tier destination for the Constellation Program, in part because of its immense pyroclastic vent, which is the largest indigenous source of volatiles in the south polar region (Kring et al., 2014).

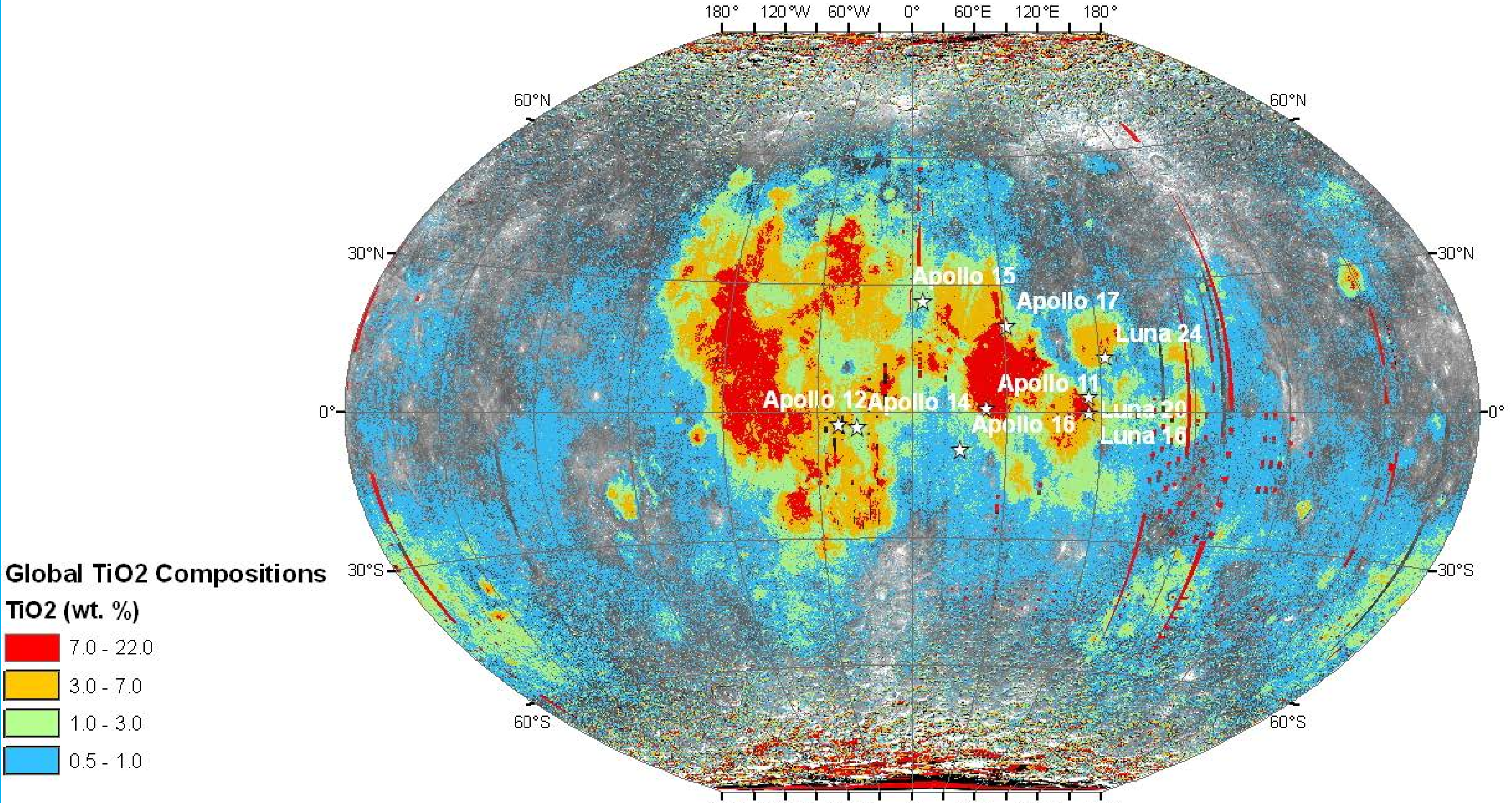
Mare Basalt Localities, Including Detections of Cryptomare

Previously mapped mare and recently detected cryptomare (Whitten & Head 2015) cover 18% of the Moon's surface. A gravity survey suggests a similar result between 17.9 and 19.5% (Sori et al. 2016).

Most mare occur on the nearside of the Moon.



Mare Basalt TiO_2 Abundances Estimated from Orbit



Created by Katie Singer
Data: LPI Clementine Mapping Project- FeO and TiO2 using Lucey et al. [2000] method

Producing Water from Ilmenite ($FeTiO_3$) Extracted from Mare Basalts

Using H_2 as the reductant (hydrogen reduction).

Single step process: $FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$

For that portion of H_2O that is split for the product O_2, H_2 can be recycled.

Using C as the reductant (carbothermal reduction).

Step 1: $FeTiO_3 + (1+x)C \rightarrow FeC_x + CO + TiO_2$

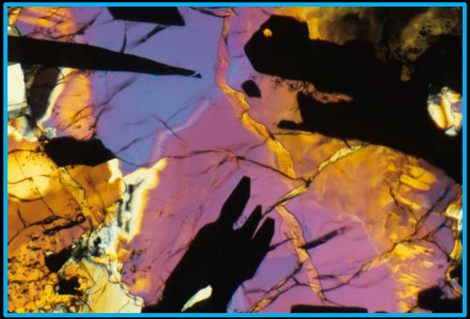
Step 2: $FeC_x + x/2O_2 \rightarrow Fe + xCO$

Step 3: $yCO + (2y+1)H_2 \rightarrow yH_2O + C_yH_{2y+2}$

Step 4: $C_yH_{2y+2} \rightarrow C_y + (y+1)H_2$

If H_2O is split for the product O_2, then H_2 and C can be recycled.

An example of an ilmenite-bearing mare basalt is Apollo sample 70017. In this microscopic view, ilmenite is the opaque (black-looking) mineral. The field of view is 2.1 mm wide.


David A. Kring

Note: Not all mare basalts have ilmenite ($FeTiO_3$).

7

Ongoing impacts, including micrometeoritic impacts, have infused the regolith with meteoritic-derived volatile abundances. Those volatiles, when combined with volatiles from the solar wind, provide a recoverable reservoir everywhere on the Moon. They have also infused the soil with meteoritic metal, which is another potential resource for a sustainable exploration program.

Regolith and Underlying Structure

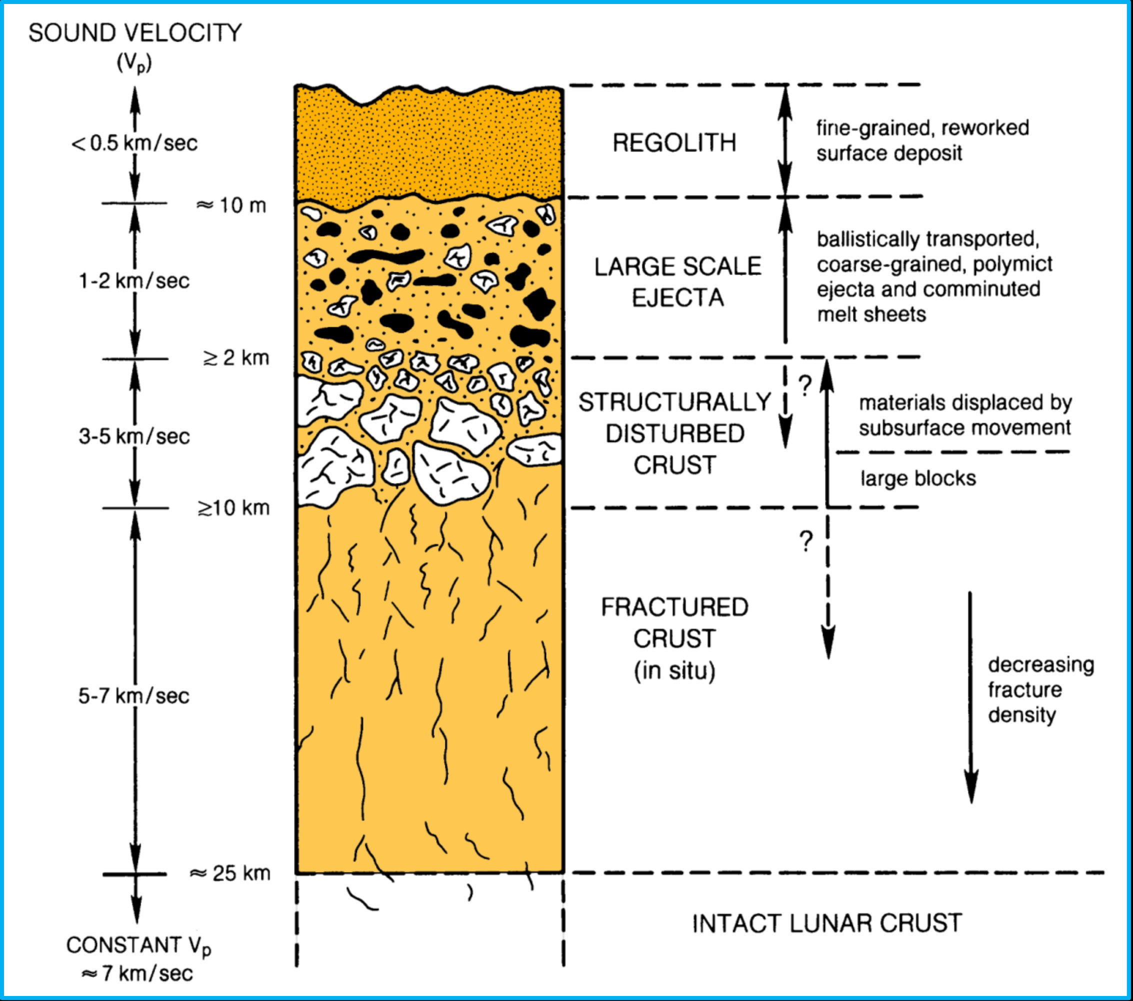
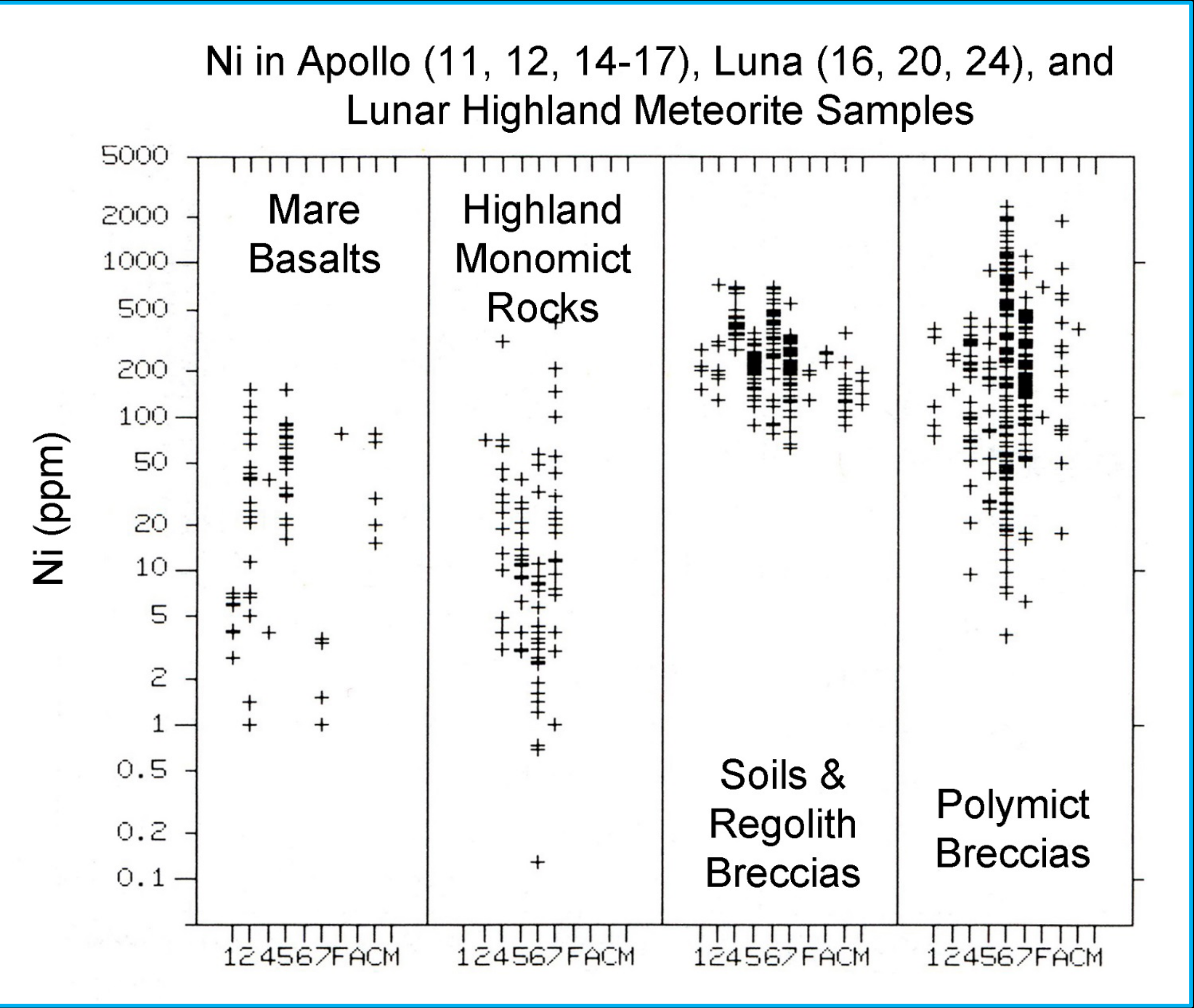


Illustration credit: Friedrich Hörz (NASA JSC)

Lunar Regolith

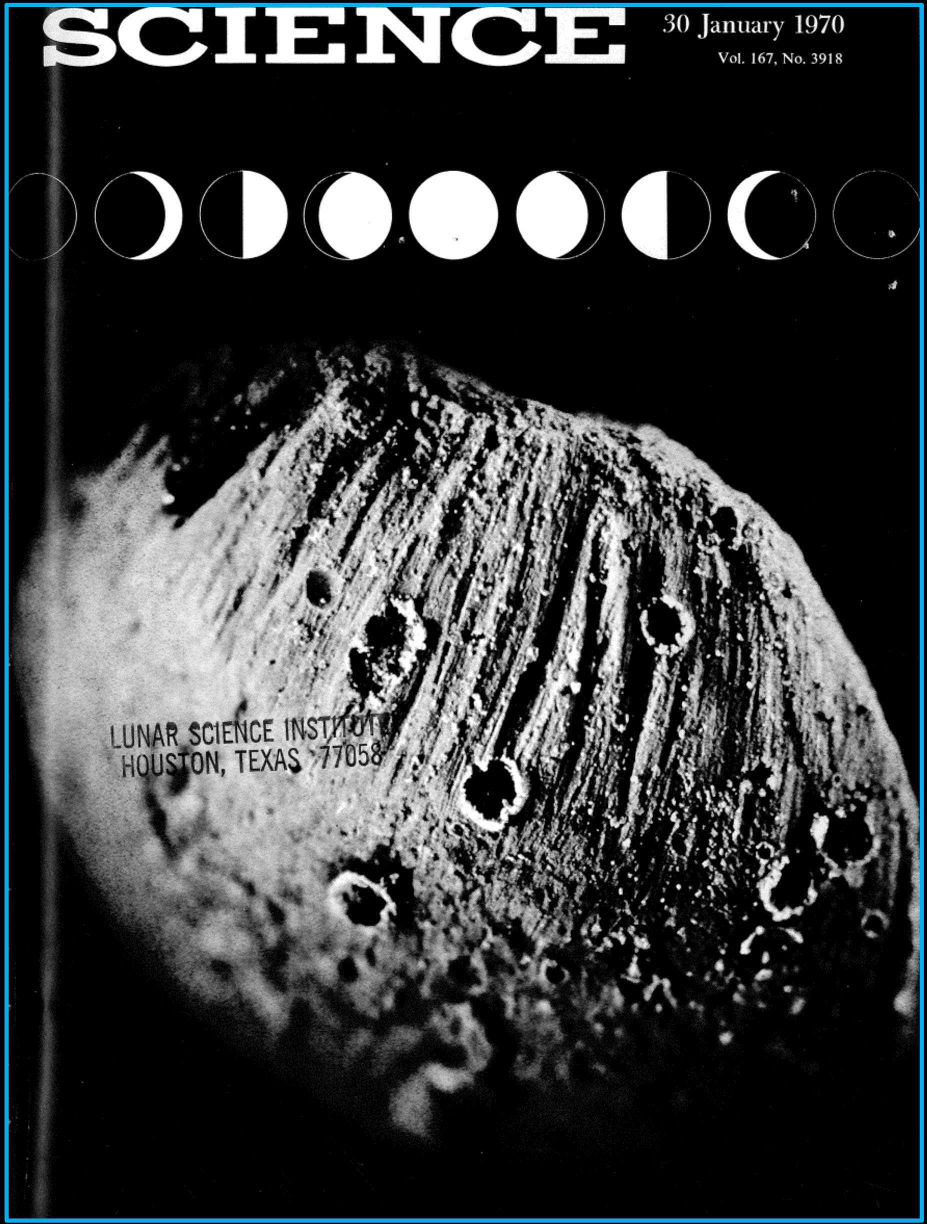
The regolith is the uppermost layer in a sequence of units affected by over 4 billion years of impact cratering processes.

In general, the regolith is a unit a few meters thick.



Haskin & Warren (1991) Lunar Sourcebook.

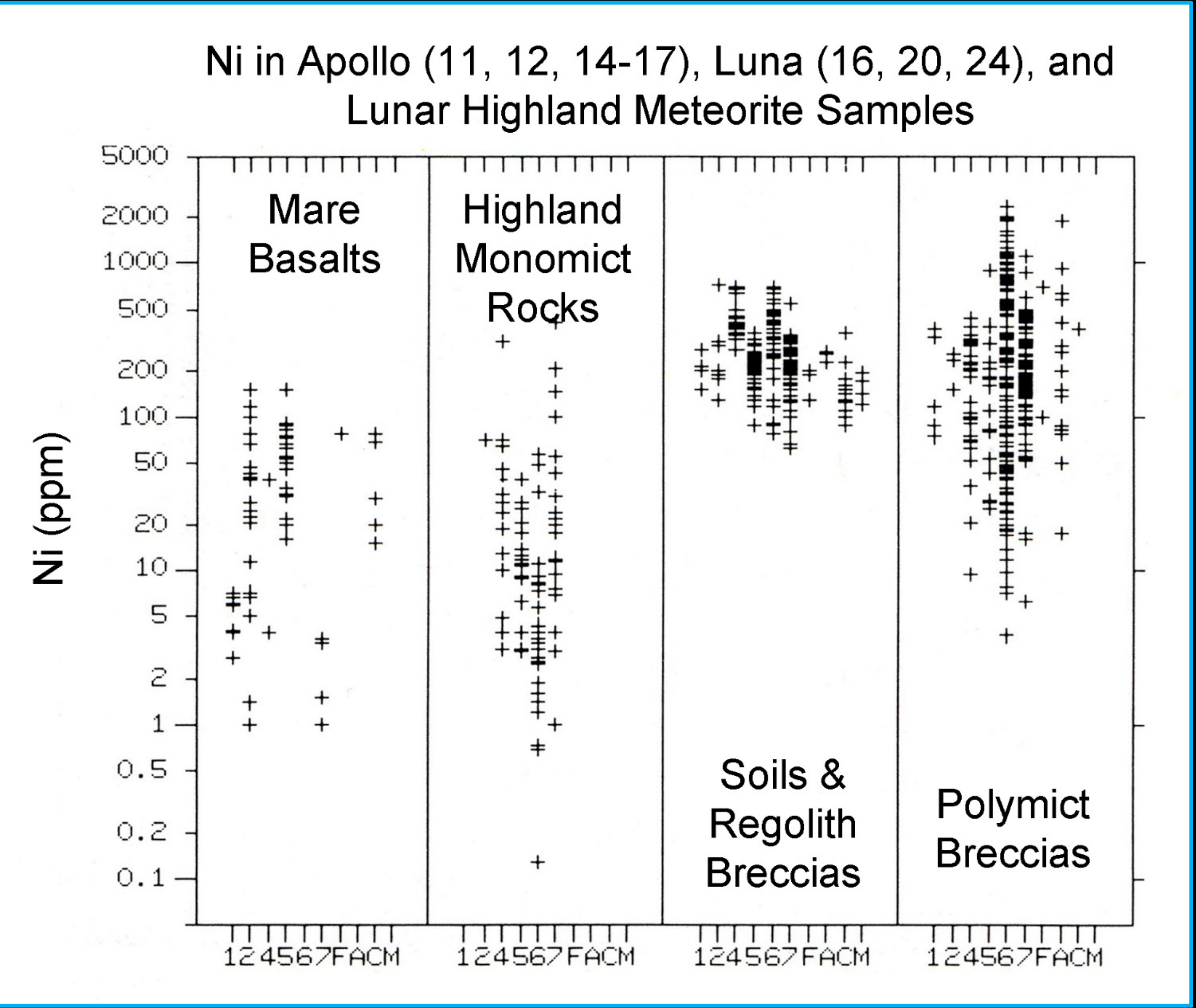
Meteoritic debris is responsible for ~1 to 2% of the chemical constituents of lunar soils.



Meteoritic debris is responsible for ~1 to 2% of the chemical constituents of lunar soils.

Meteoritic 'contamination' was immediately obvious and featured on the cover of the Apollo 11 special issue of *Science* in January 1970.

A particle of meteoritic Fe-Ni-rich metal is shown, delivered by impacting debris, and subsequently cratered by smaller impacting debris.

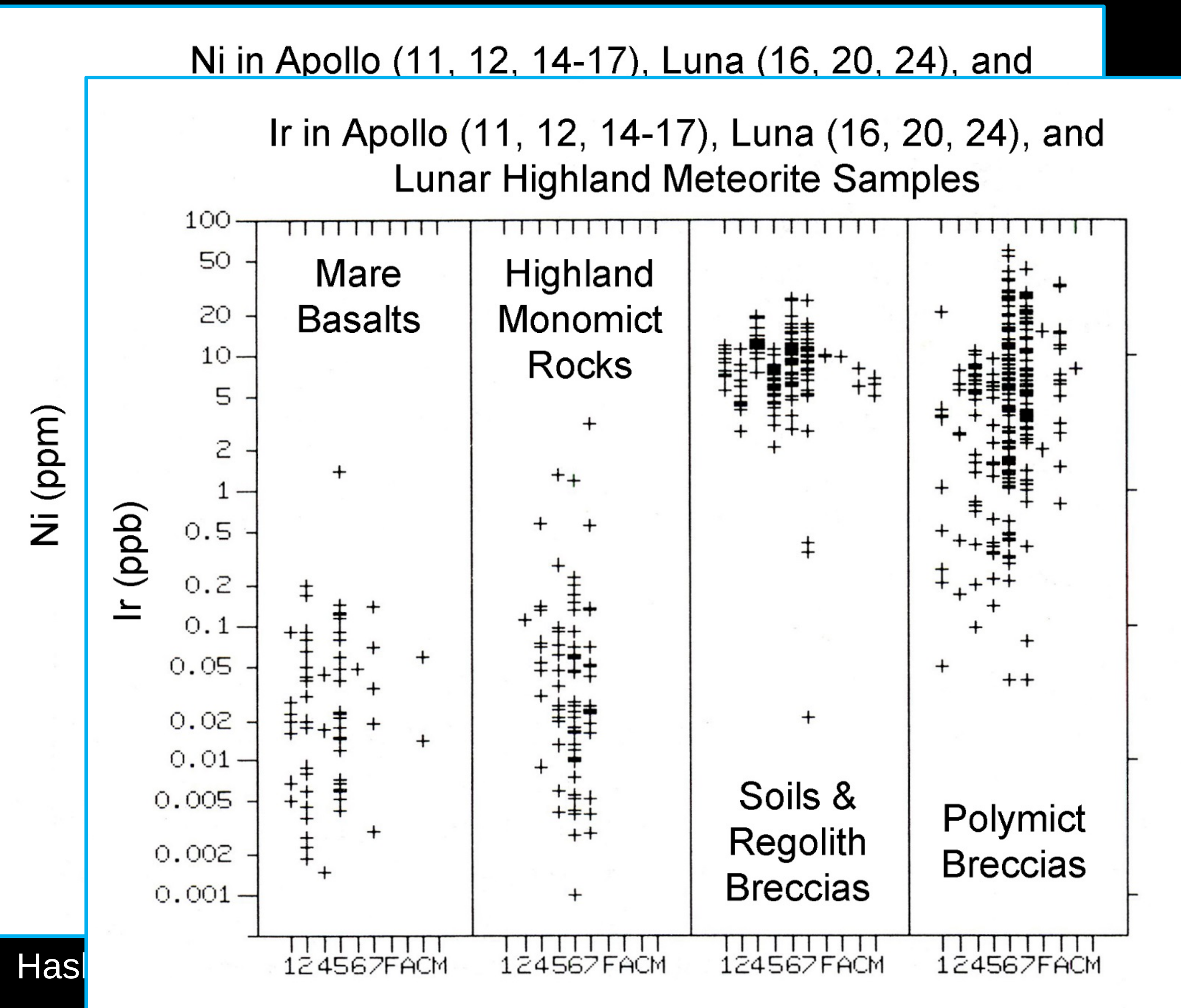


Haskin & Warren (1991) Lunar Sourcebook.

Meteoritic debris is responsible for ~1 to 2% of the chemical constituents of lunar soils.

This contribution is most easily seen with ‘contaminating’ siderophile elements, like Ni and platinum group elements (PGEs), because much of the Moon’s siderophile elements are sequestered in the core and mantle.

Pristine (uncontaminated) crustal rocks have very little Ni and PGEs.



Of these elements, iridium may be the most famous, because it is produced the anomalous signature of impact on Earth that produced the extinction of dinosaurs and most life 66 million years ago.

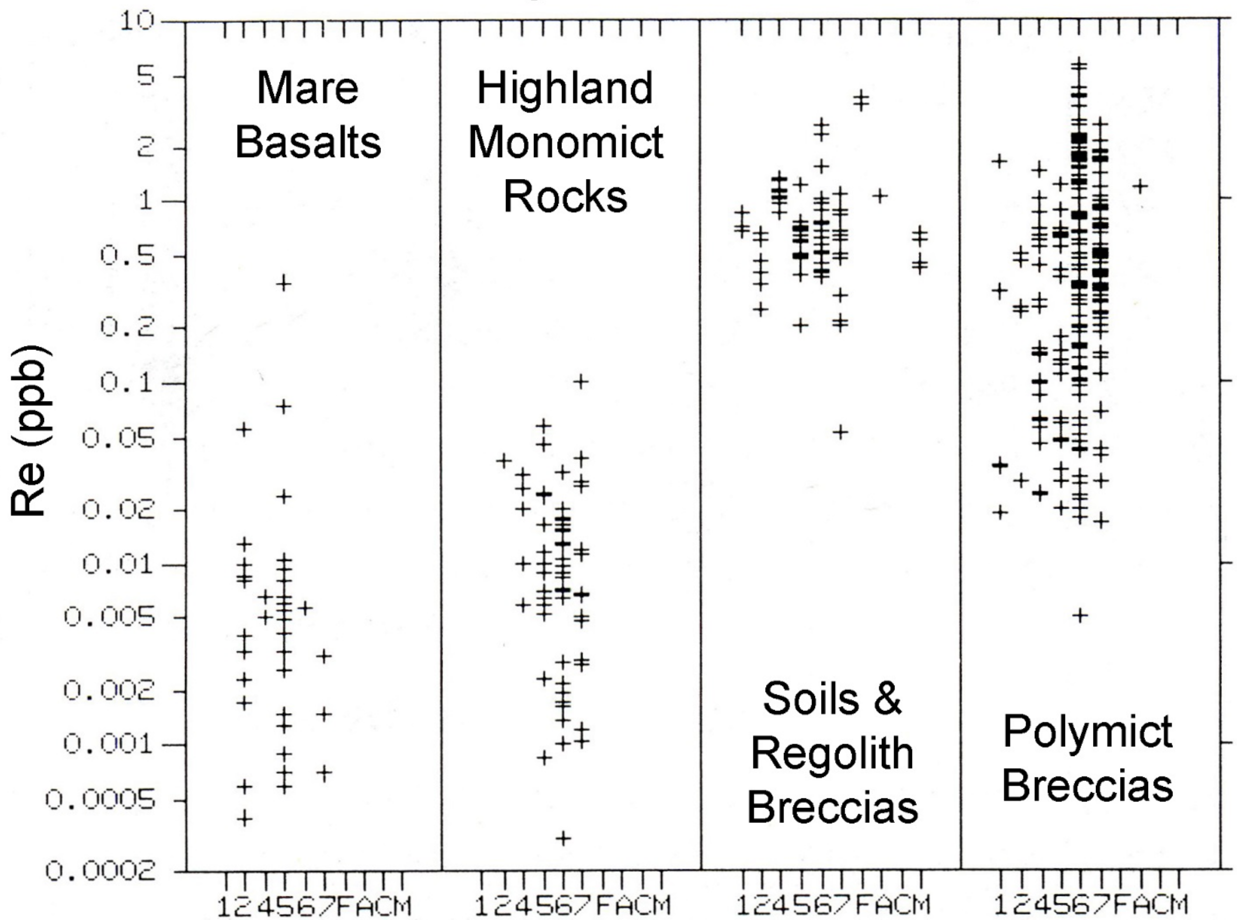
Meteoritic, asteroidal, and cometary impact delivers PGEs to a planetary surface, like that of the Moon.

Ni in Apollo (11, 12, 14-17), Luna (16, 20, 24), and

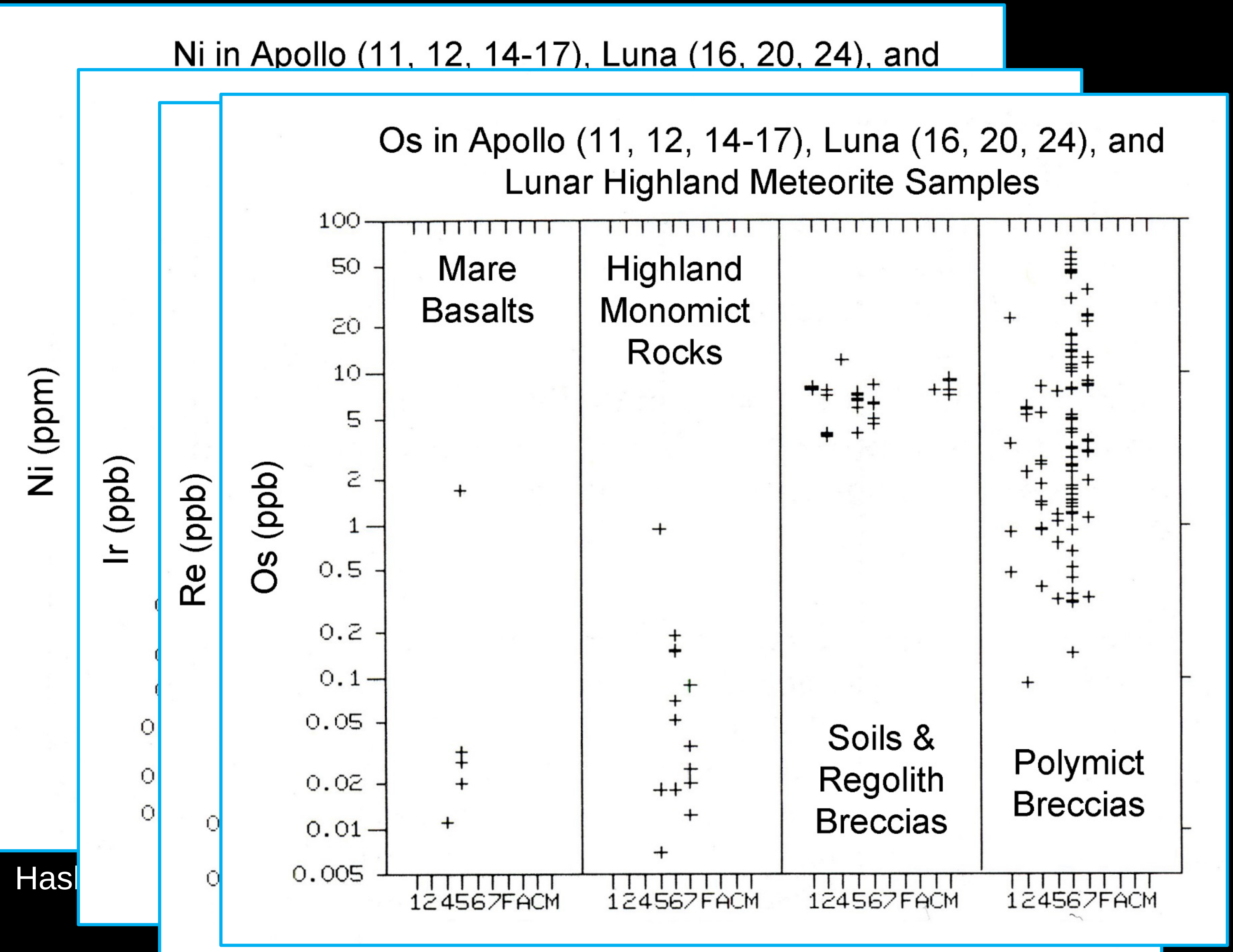
Ni (ppm)

Ir (ppb)

Re in Apollo (11, 12, 14-17), Luna (16, 20, 24), and Lunar Highland Meteorite Samples



Hasl


Ni in Apollo (11, 12, 14-17), Luna (16, 20, 24), and
Ni (ppm)
Ir (ppb)
Re (ppb)
Os in Apollo (11, 12, 14-17), Luna (16, 20, 24), and
Lunar Highland Meteorite Samples
Os (ppb)
100
50
20
10
5
2
1
0.5
0.2
0.1
0.05
0.02
0.01
0.005
Mare Basalts
Highland Monomict Rocks
Soils & Regolith Breccias
Polymict Breccias
124567FACM
124567FACM
124567FACM
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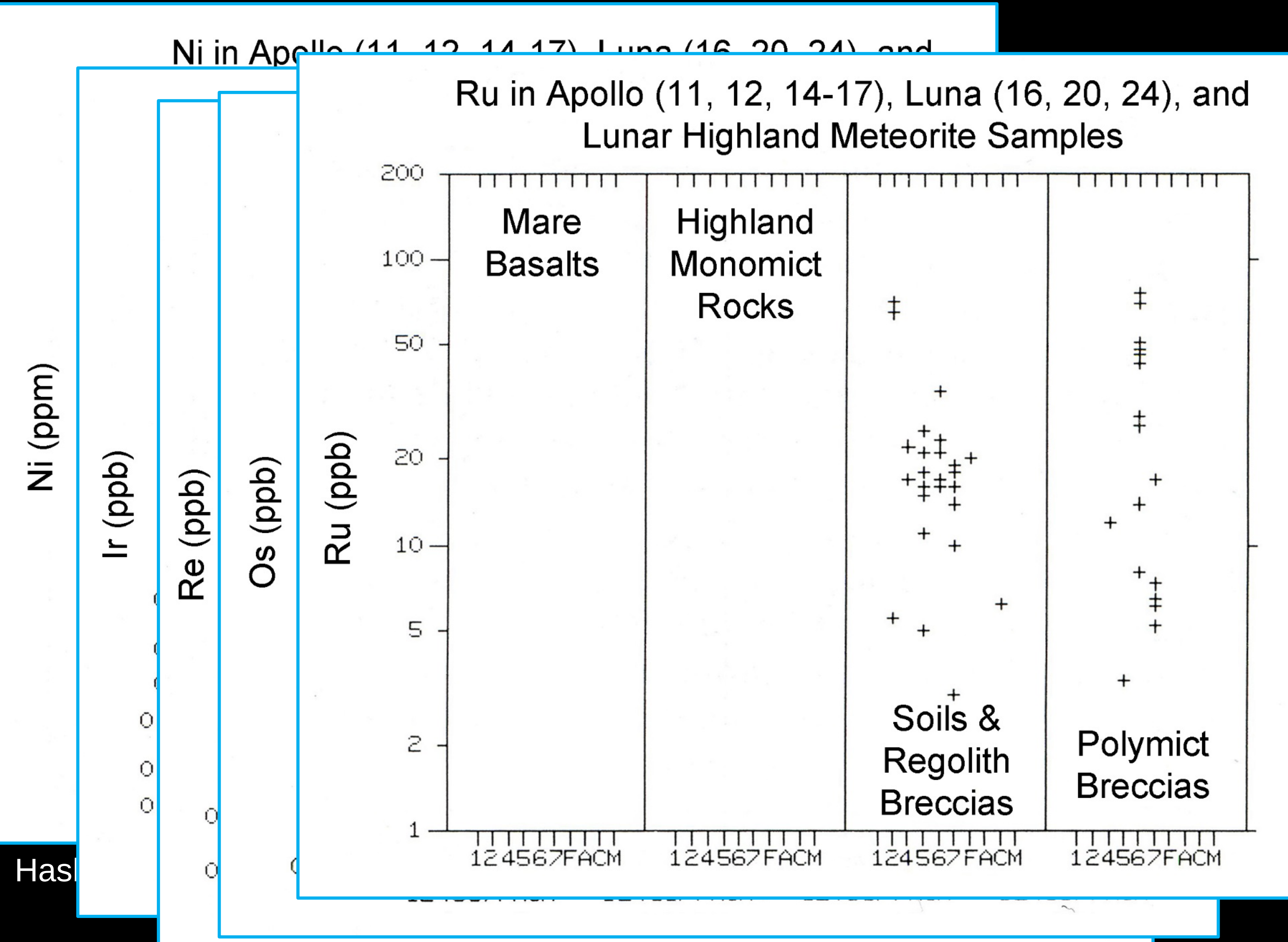
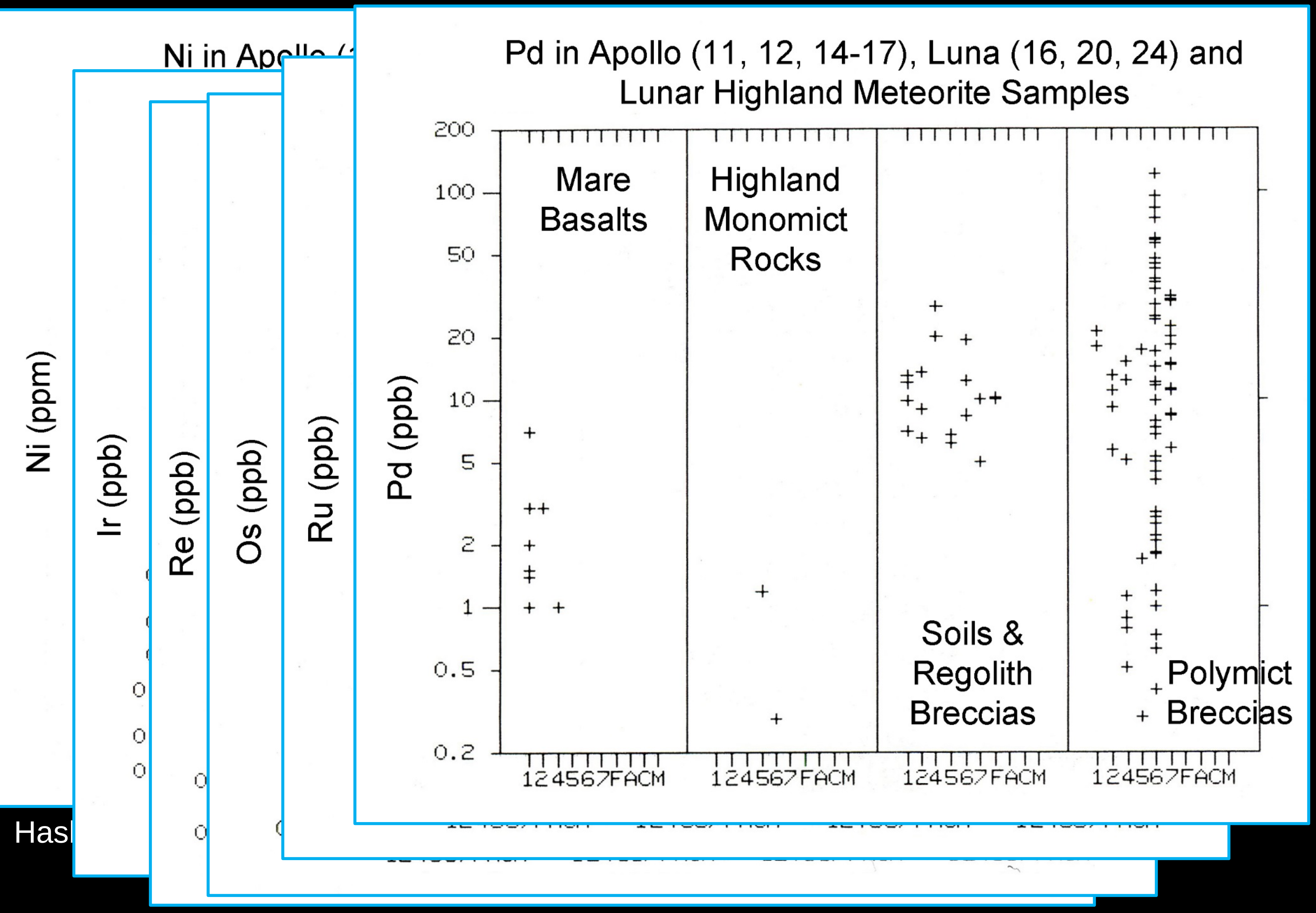

Ni in Apollo (11, 12, 14-17), Luna (16, 20, 24), and
Ni (ppm)
Ir (ppb)
Re (ppb)
Os (ppb)
Ru in Apollo (11, 12, 14-17), Luna (16, 20, 24), and Lunar Highland Meteorite Samples
Ru (ppb)
200
100
50
20
10
5
2
1
Mare Basalts
Highland Monomict Rocks
Soils & Regolith Breccias
Polymict Breccias
124567FACM
124567FACM
124567FACM
124567FACM
Hasl


Ni in Apollo (1
Ni (ppm)
Ir (ppb)
Re (ppb)
Os (ppb)
Ru (ppb)
Pd in Apollo (11, 12, 14-17), Luna (16, 20, 24) and
Lunar Highland Meteorite Samples
Pd (ppb)
200
100
50
20
10
5
2
1
0.5
0.2
Mare
Basalts
Highland
Monomict
Rocks
Soils &
Regolith
Breccias
Polymict
Breccias
124567FACM
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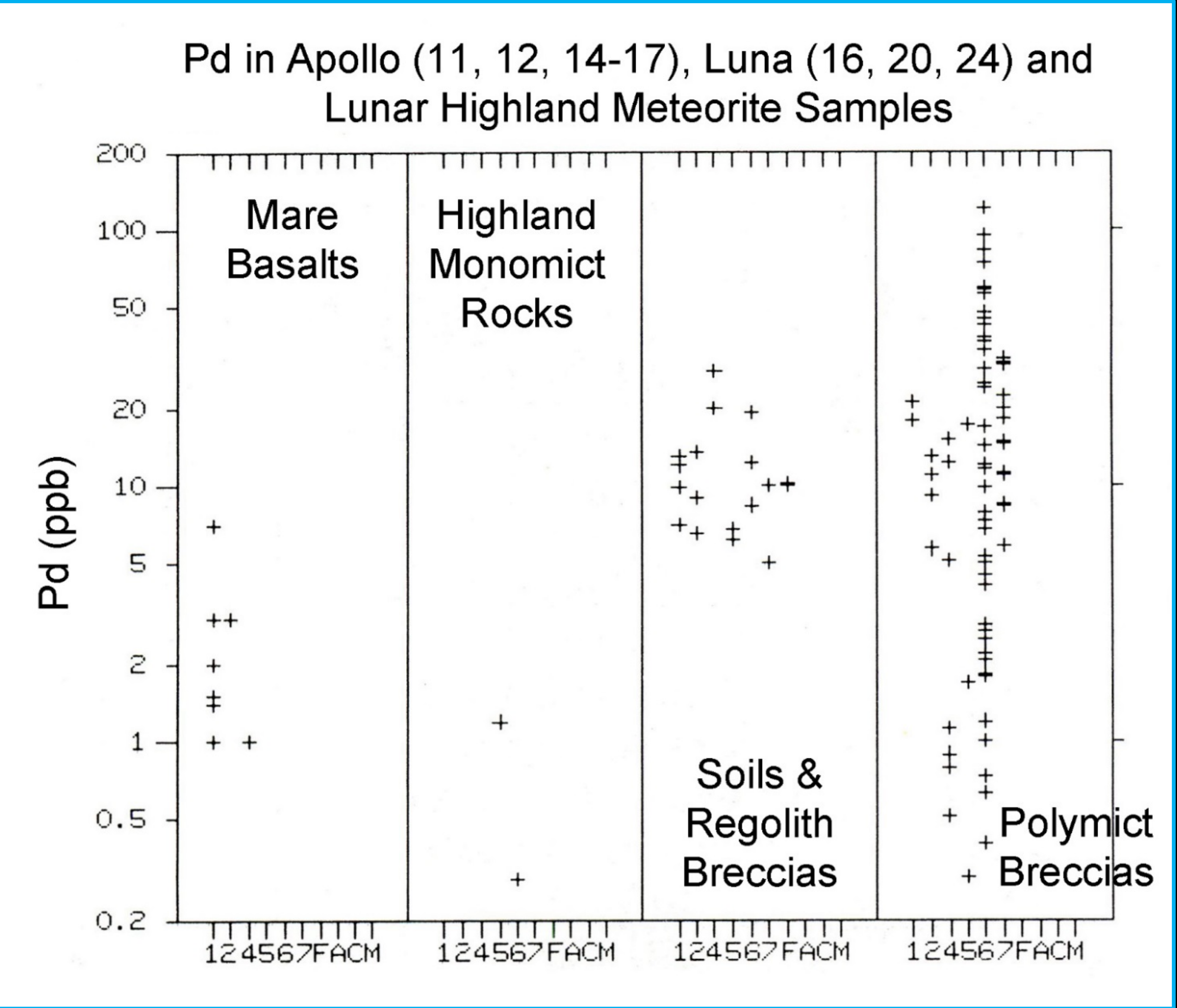
124567FACM
Hasl



Haskin & Warren (1991) Lunar Sourcebook.

Despite lunar regolith enrichments in PGEs, like Pd, their abundances are much less than those in terrestrial ore bodies.

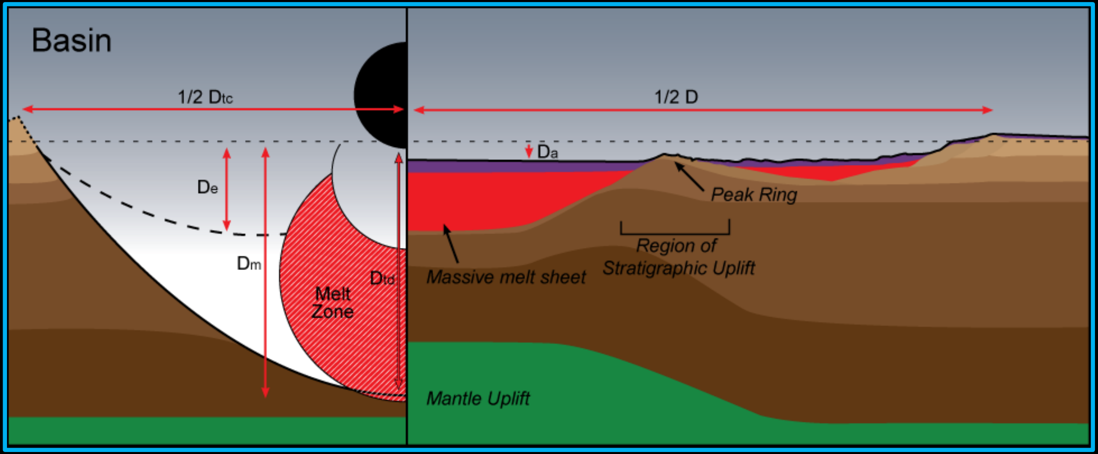
Pd abundances in the Sudbury Offset Dike ores are about 1000 ppb (or 10 times higher than the richest polymict breccia)

Nonetheless, because regolith is easily accessible and because metal can be easily separated from silicates in the regolith, it may – at some point in the future – have an economically viable potential.

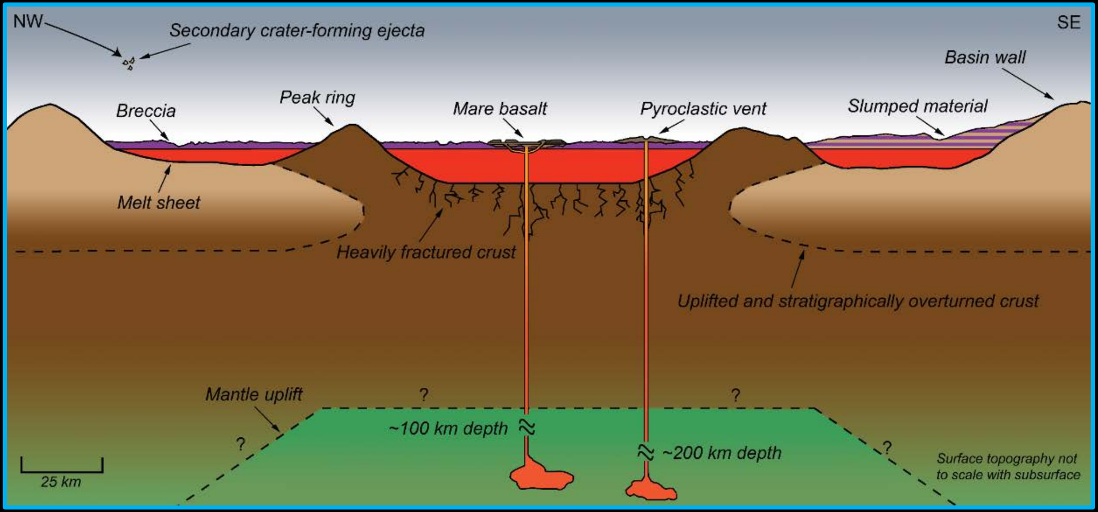
8

The largest of those impacts produced melt sheets that may have differentiated, potentially forming ore deposits of metal and sulfide.

An Alternative Setting for PGEs – Impact Melt Sheets



LPI (Jilly & Kring, after Cintala & Grieve)



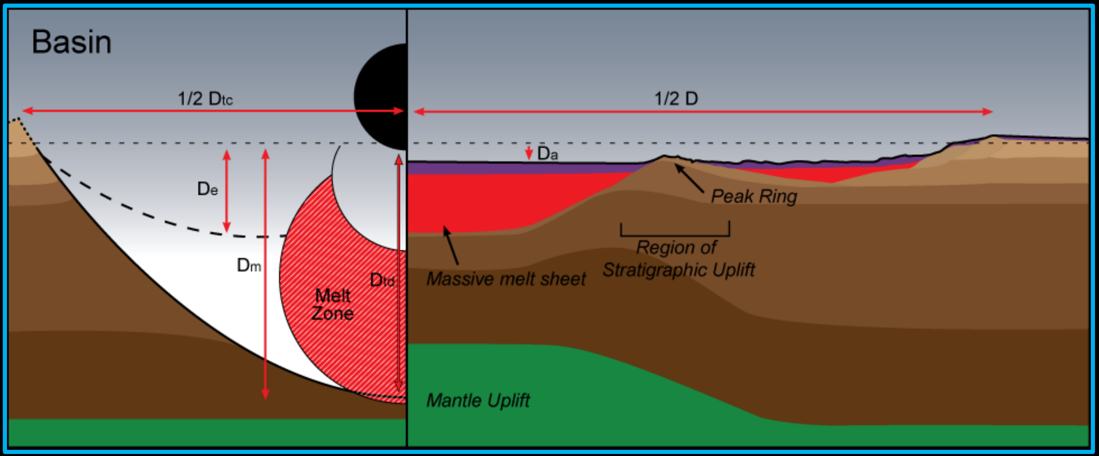
Steenstra et al. (Adv. Space Res. 2016)

Impact Melt Sheet Ores

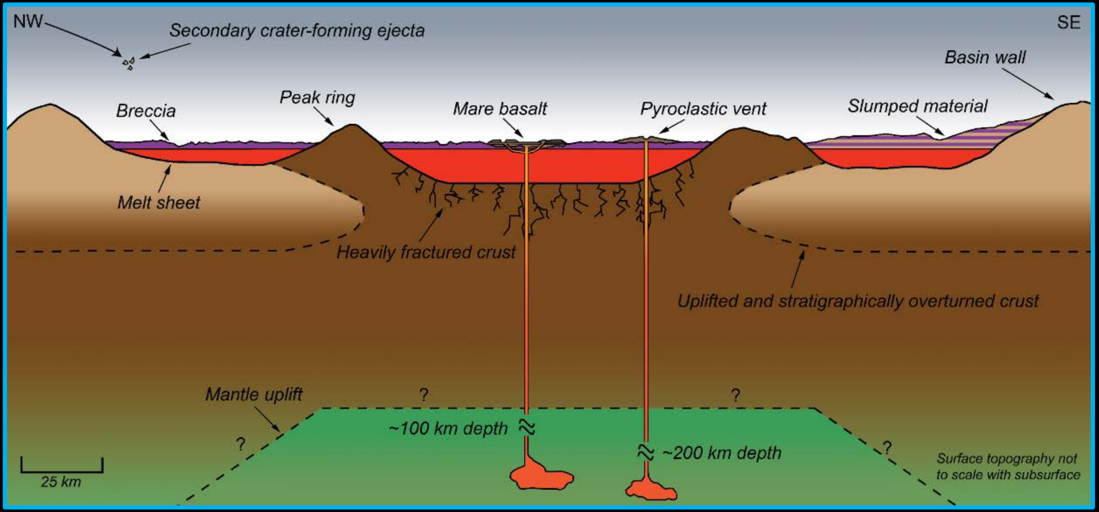
The Sudbury impact structure on Earth contains the second largest reserves of Ni and the third largest reserves of PGEs.

The ore was produced by an impact event, but most of the ore-forming elements were scavenged from the crust, rather than delivered by the impactor.

An Alternative Setting for PGEs – Impact Melt Sheets



LPI (Jilly & Kring, after Cintala & Grieve)



Steenstra et al. (Adv. Space Res. 2016)

Impact Melt Sheet Ores

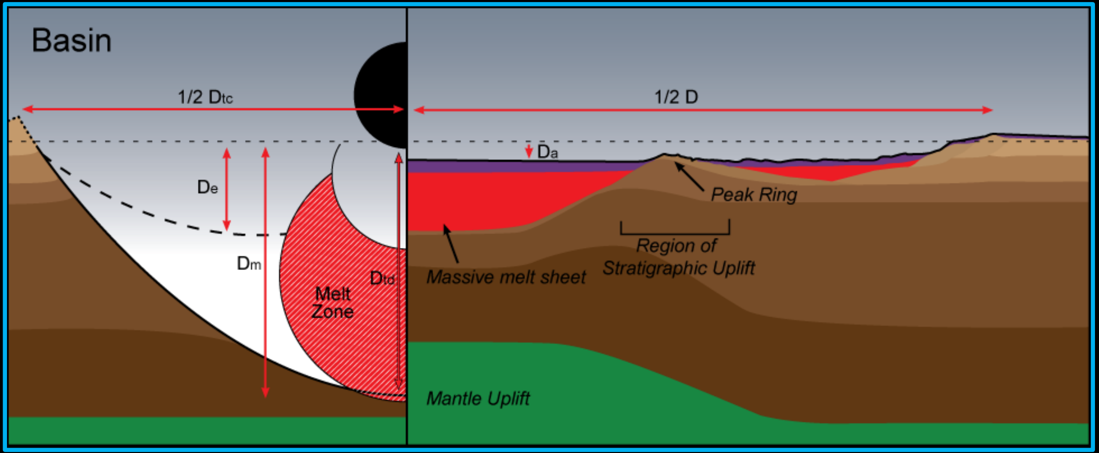
In the case of Sudbury, the impact event melted a large volume of the crust.

The impact melt sheet at Sudbury then differentiated.

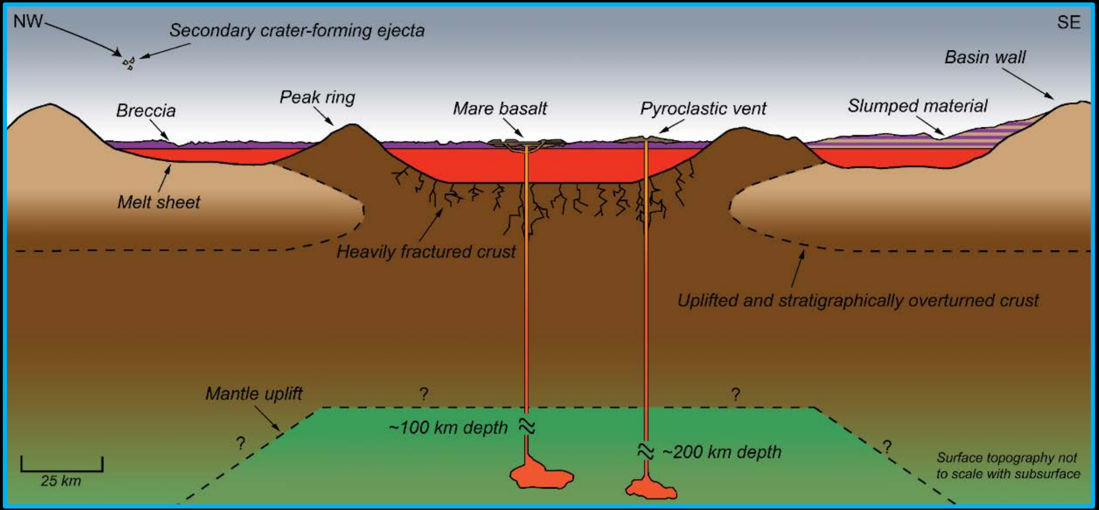
Precipitating sulfides, with Ni-Cu-(PGE), were denser than the silicate-dominated impact melt and sank, forming concentrated ore bodies.

Hydrothermal processes also concentrated some ore.

An Alternative Setting for PGEs – Impact Melt Sheets



LPI (Jilly & Kring, after Cintala & Grieve)



Steenstra et al. (Adv. Space Res. 2016)

Impact Melt Sheet Ores

Is the source of PGEs in potential ores the same on the Moon?

Impactor concentration in impact melts is usually 1% to <<1%.

On the Moon, target (crustal) PGE abundance is so low that impactor PGEs may dominate melt PGEs.

To illustrate the relative roles of the two sources, the PGE iridium (Ir) is utilized on the next two slides.

An Alternative Setting for PGEs – Impact Melt Sheets

If we assume chondritic (type CI) composition impactors, then……

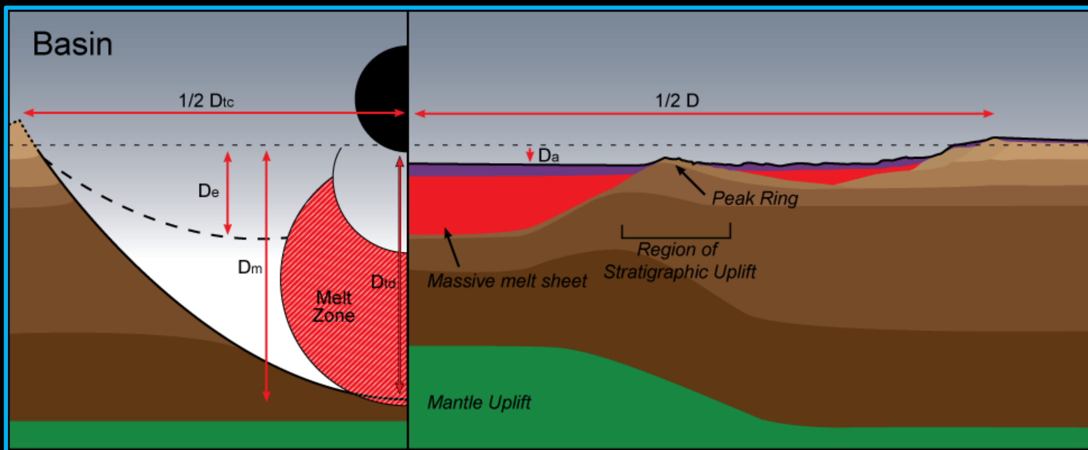
Target (lunar crust) Ir (ppb)	Impactor Ir (ppb)	Impactor fraction in melt (%)	Ir fraction from impactor (%)
0.001	450	0.001	81.82
0.001	450	0.01	97.83
0.001	450	0.1	99.78
0.001	450	1	99.98
0.01	450	0.001	4.31
0.01	450	0.01	31.03
0.01	450	0.1	81.82
0.01	450	1	97.82
1	450	0.001	0.45
1	450	0.01	4.31
1	450	0.1	31.03
1	450	1	81.82

An Alternative Setting for PGEs – Impact Melt Sheets

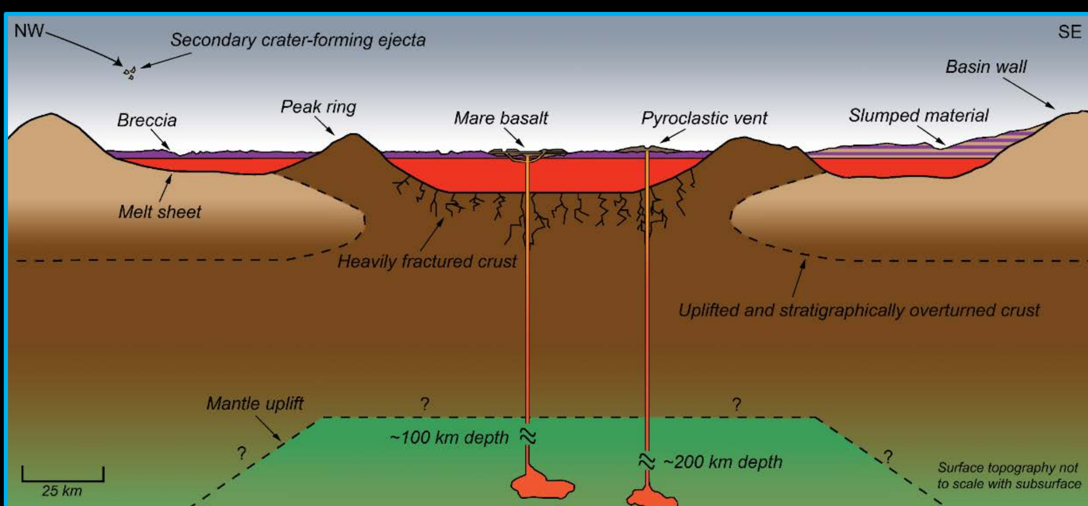
If we assume iron (type IAB) composition impactors, then……

Target (lunar crust) Ir (ppb)	Impactor Ir (ppb)	Impactor fraction in melt (%)	Ir fraction from impactor (%)
0.001	3100	0.001	96.88
0.001	3100	0.01	99.68
0.001	3100	0.1	99.98
0.001	3100	1	100.
0.01	3100	0.001	23.66
0.01	3100	0.01	75.61
0.01	3100	0.1	96.88
0.01	3100	1	99.68
1	3100	0.001	3.01
1	3100	0.01	23.66
1	3100	0.1	75.61
1	3100	1	96.88

An Alternative Setting for PGEs – Impact Melt Sheets



LPI (Jilly & Kring, after Cintala & Grieve)



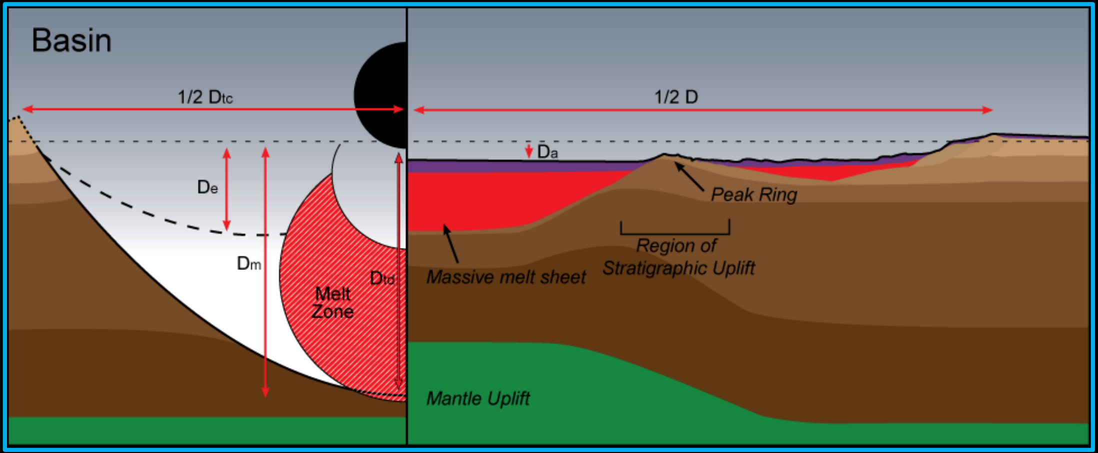
Steenstra et al. (Adv. Space Res. 2016)

Impact Melt Sheet Ores

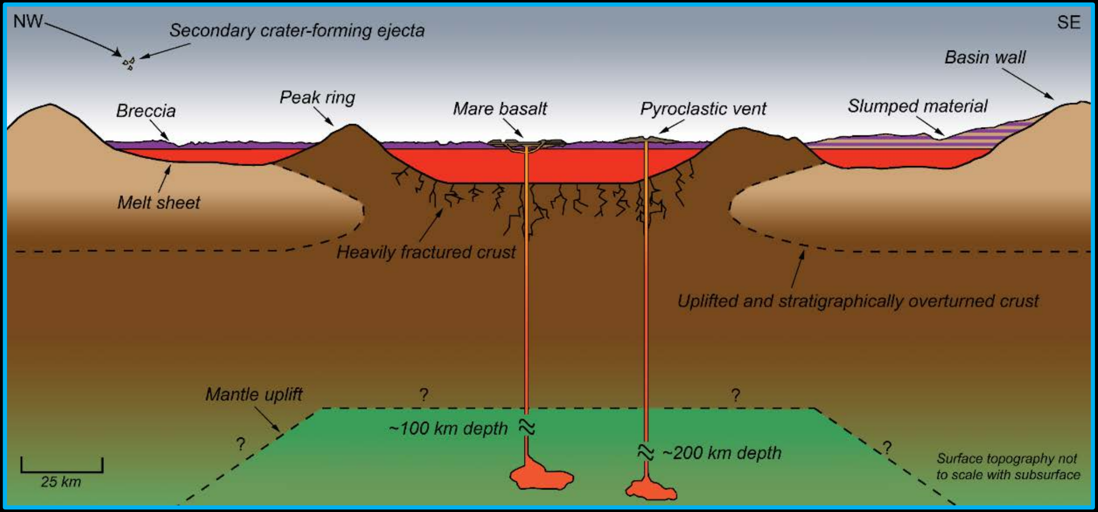
Impact melt sheet differentiation process may not be as effective on the Moon as on Earth, because of lower gravity.

Nor has evidence of the differentiation process yet been found on the Moon; it is one of the important unsolved issues identified by the National Research Council (2007) for exploration of the Moon.

An Alternative Setting for PGEs – Impact Melt Sheets



LPI (Jilly & Kring, after Cintala & Grieve)



Steenstra et al. (Adv. Space Res. 2016)

Impact Melt Sheet Ores

A theoretical study by Cintala & Grieve (1998) suggest differentiation may occur if melt sheets exceed 1 km thickness; i.e., it may occur in impact basins (>300 km diameter) of which there are about 50.

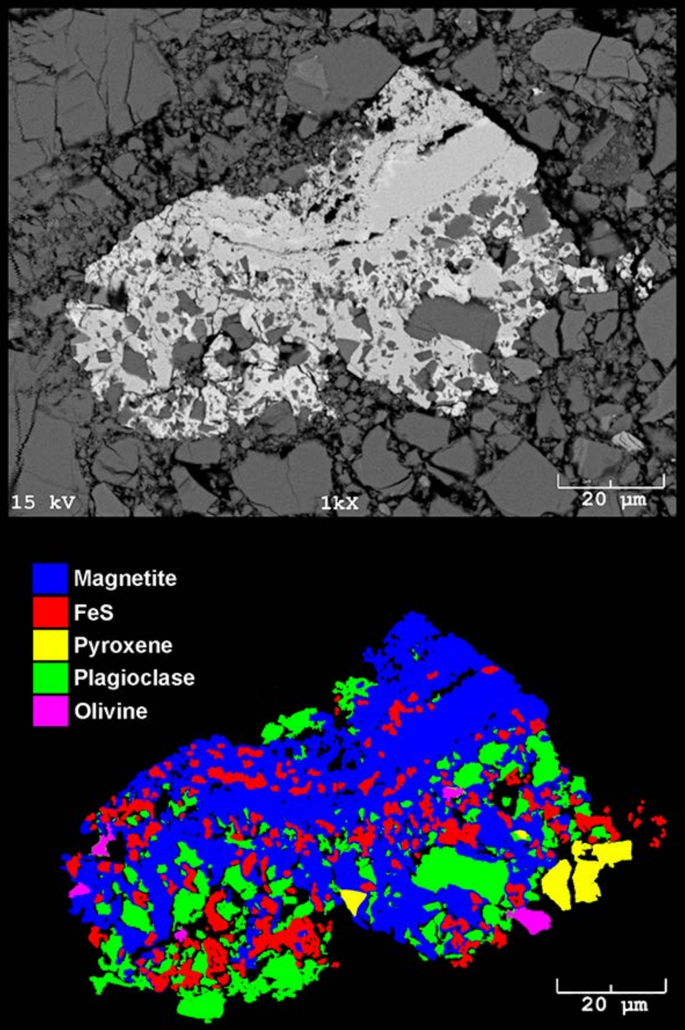
It may be difficult to recover ore from the base of a lunar impact melt sheet.

One may need to rely on a younger impact event that excavated potential PGE-rich differentiates. Thus far, none have been detected on the lunar surface.

Final words:

Be prepared to be surprised.

Hints of Fluid Mobility in the Lunar Crust



Joy et al. (2015)

- Shearer et al. (2012 and reference therein) describe sulfide mobility and deposition in shallow lunar crustal environments.
- Treiman et al. (2014) describe impact-induced remobilization of volatiles that led to the precipitation of fluorapatite ($Ca_5(PO_4)_3(F,C,OH)$).
- Joy et al. (2015) describe magnetite that may have been produced by reactions involving H_2O steam/liquid or CO_2 gas, potentially via vapor transport triggered by magmatic degassing or, alternatively, by an impacting asteroid or comet.

Be prepared to be surprised by new discoveries during a lunar surface exploration program.

Many of the illustrations utilized in today's lecture
are available in the

LPI Library of Classroom Illustrations

https://www.lpi.usra.edu/exploration/training/resources/?view=illustrations

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Recommended Reading

There are three classic books about lunar geologic history:

S. R. Taylor (1982) *Planetary Science: A Lunar Perspective*. Lunar and Planetary Institute, Houston TX. (The book is out of print, but is still available electronically at https://www.lpi.usra.edu/publications/books/).

D. E. Wilhelms (1987) *The Geologic History of the Moon*. U.S. Geological Survey Professional Paper 1348, Washington DC. (The book is out of print, but is still available electronically at https://pubs.er.usgs.gov/publication/pp1348).

G. H. Heiken, D. Vaniman, B. M. French (1991) *Lunar Sourcebook: A User's Guide to the Moon*. Lunar and Planetary Institute, Houston TX. (The book is out of print, but still available electronically at https://www.lpi.usra.edu/publications/books/).

Ross Taylor augmented his book with several journal-length summaries, such as

S. R. Taylor (2008) The Origin and Evolution of the Moon in a Planetary Context. *Golden Jubilee Memoir of The Geological Society of India*, No. 66, pp. 13-50.

S. R. Taylor (2014) The Moon re-examined, *Geochimica et Cosmochimica Acta 141*, 670-676.

Graham Ryder also provided a short supplement to Taylor's (1982) book:

G. Ryder (1987) The Moon. *Reviews of Geophysics 25(2)*, 277-284.

Recommended Reading

As part of a community-wide initiative, a review book was published:

B. J. Jolliff, M. A. Wieczorek, C. K. Shearer, and C. R. Neal, editors (2006) *New Views of the Moon*. Reviews in Mineralogy and Geochemistry, volume 60. Mineralogical Society of America.

The first chapter of that volume is:

H. Hiesinger and J. W. Head III (2006) New views of lunar geoscience: An introduction and overview. In *New Views of the Moon*, B. J. Jolliff et al. (eds.), Reviews of Mineralogy and Geochemistry, vol. 60, pp. 1-81, Mineralogical Society of America.

Please note that a new book (New Views of the Moon II) is currently being prepared by the community.

Another important review of lunar geology, with an eye on future exploration, is

National Research Council (2007) *The Scientific Context for Exploration of the Moon*. National Academies Press, Washington DC.

That review was recently supplemented by a SSERVI-sponsored report produced at the request of the NASA Associate Administrator of Science:

C. M. Pieters et al. (2018) *Transformative Lunar Science.*

Recommended Reading

For the purposes of the January 20, 2020 lecture "Lunar Geology," I recommend – in this order – the following brief dips into the literature

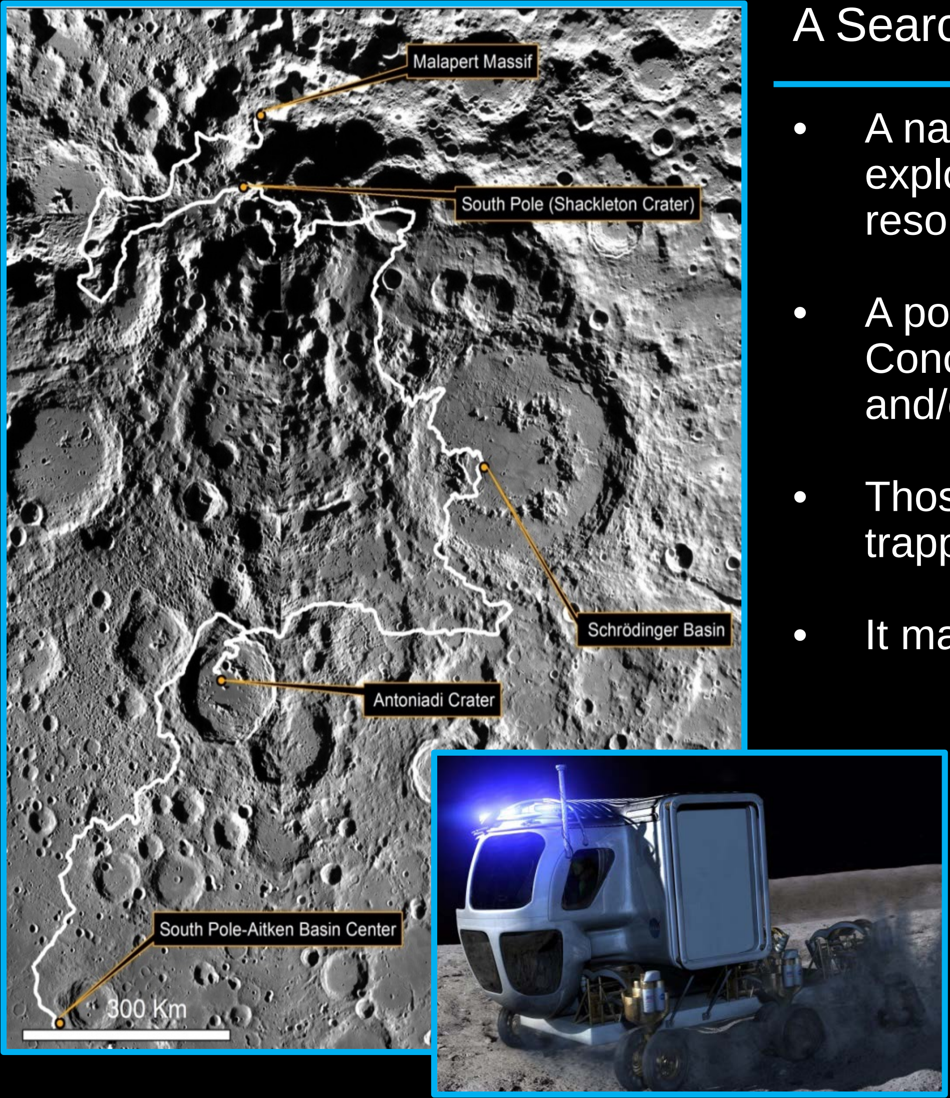
1. Hiesinger and Head (2006), 82 pages long.

2. Chapter 2 (pp. 10-19) in the NRC (2007) report.

3. Pieters et al. (2018), which is only 8 pages long.

Addendum

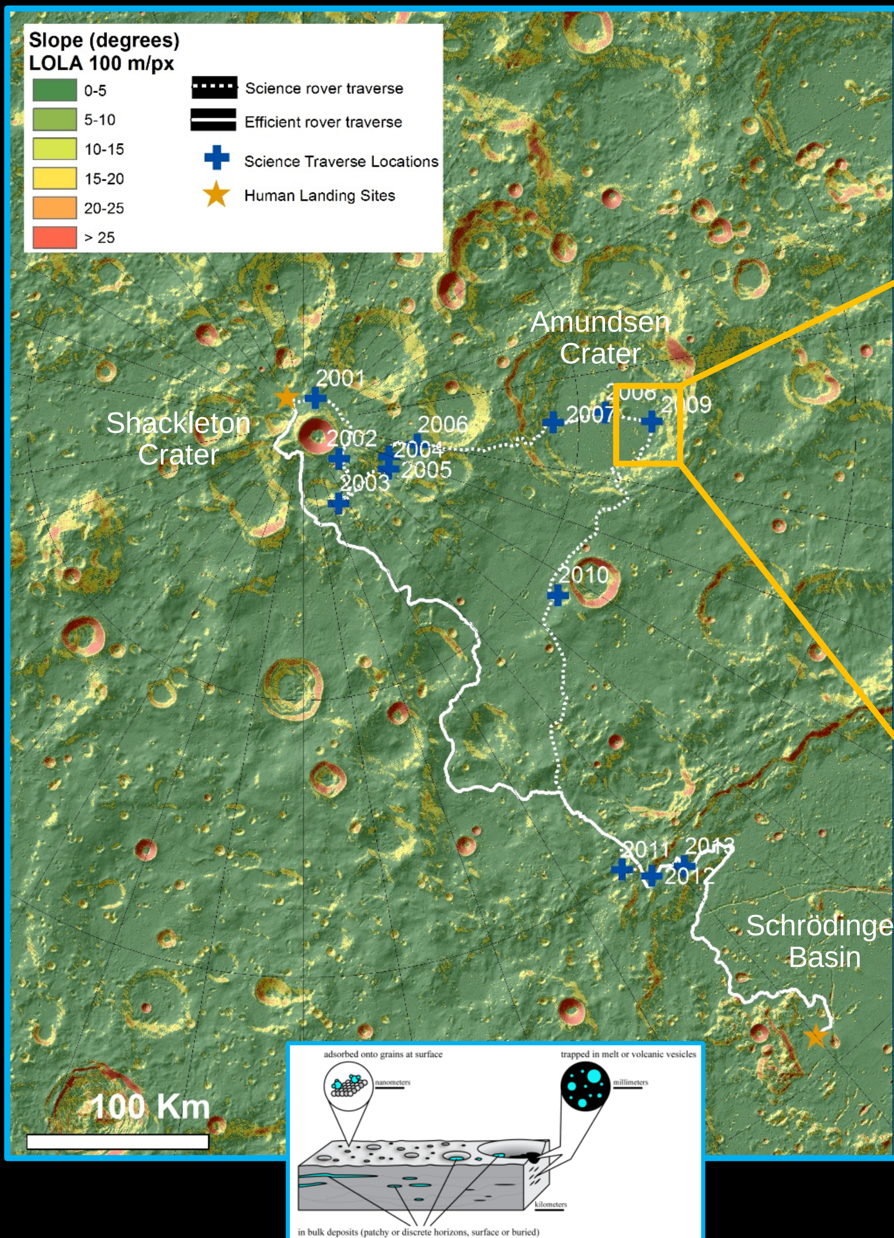
Surveying for subsurface ice deposits.

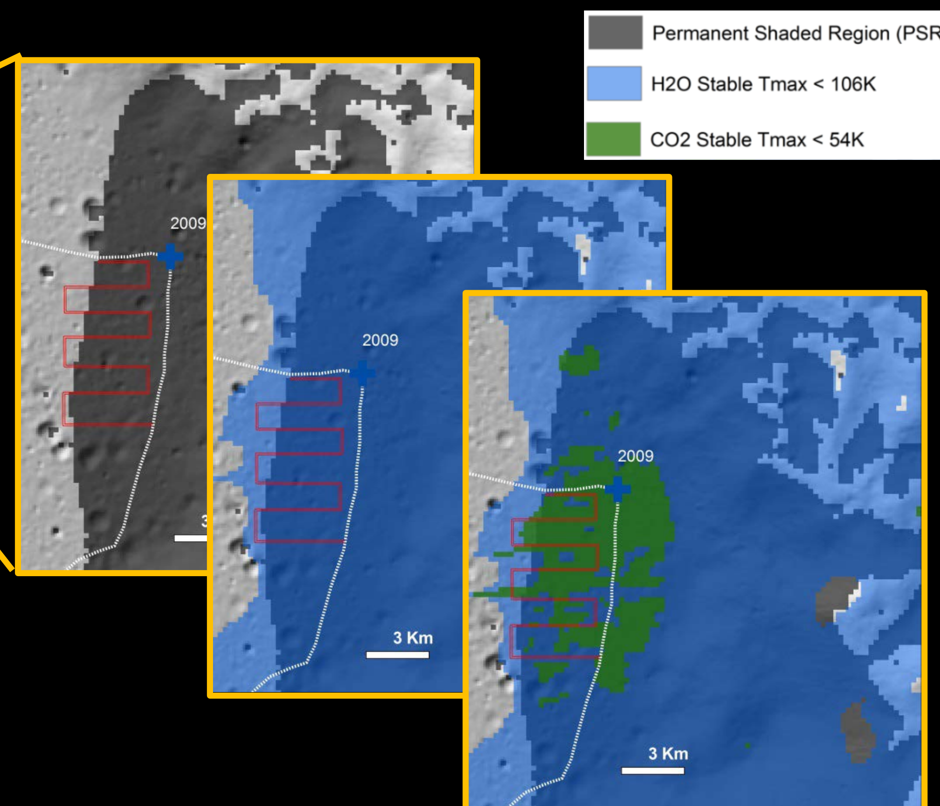


A Search for Resources

- A nationally and commercially sustainable space exploration program will be enhanced with in situ resources.
- A potential resource is ice, in subsurface deposits. Concentrated deposits of volatile ices (like H, OH, and/or H_2O) can be used for fuel and air.
- Those types of deposits would augment solar wind trapped in lunar soils.
- It may be possible to conduct surveys of potential ice deposits using re-usable rovers for astronauts.
  - Between crew landings, Houston can conduct those surveys when tele-operating the rovers to the next crew landing site.

Using Rovers to Prospect for Ice Resources between Astronaut Landing Sites





Within Amundsen Crater
GPR & NS survey of volatiles en route