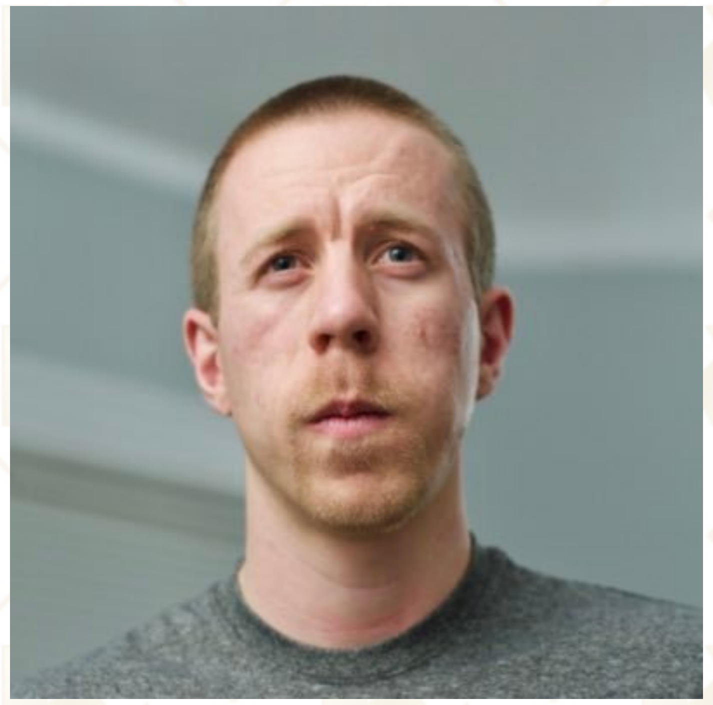
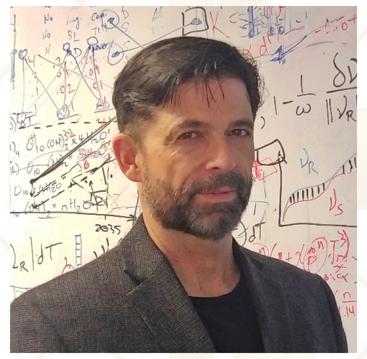
Strategic Regolith Processing on the Moon and Mars

Kevin M. Cannon, Daniel T. Britt, and Philip T. Metzger

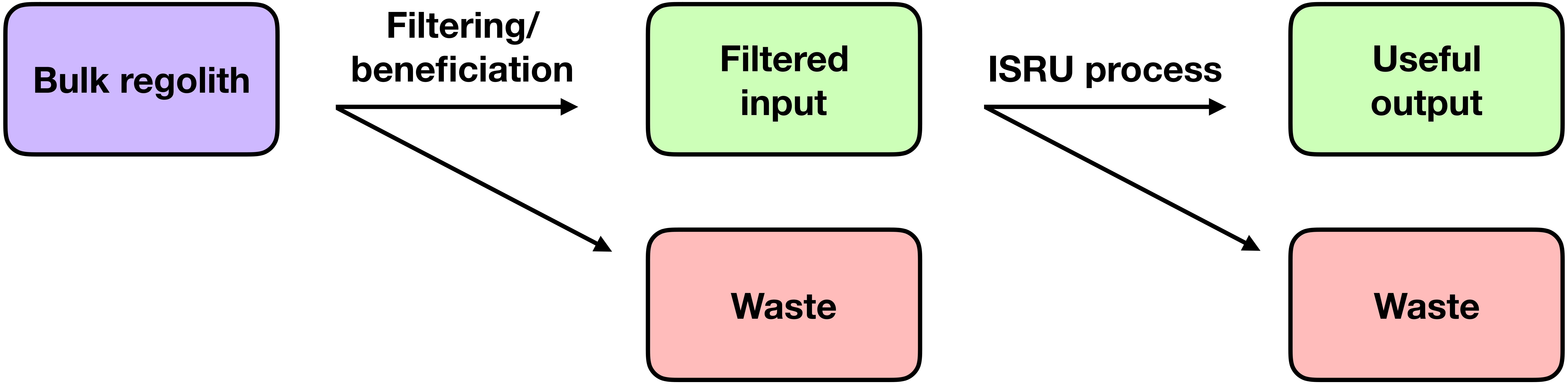


Kevin M. Cannon, Ph.D.
Planetary Scientist
University of Central Florida
cannon@ucf.edu
http://kevincannon.rocks



Ceramic honeycomb O2 extraction	Solar array production	Implanted solar wind extraction	Magnesium structures
Cement and concrete	Sponge iron process	Hydrogen reduction	Landing pads
Plasma-based rebar production	Microwave volatile extraction	Ionic liquids for O2 extraction	Graded roads
Ice as construction material	Thermal energy reservoir	Laser fabrication	Berm construction
Reinforced regolith	Vacuum pyrolysis	Regolith heat shield	Nuclear waste in glasses
Fiberglass production	Regolith bags	Combustion synthesis	Bio-ISRU for H2/O2
Carbothermal reduction	Flexlock Geomats	Electrochemical processing	Geothermite construction
Microwave sintering	Molten regolith electrolysis	Electrostatic beneficiation	Additive manufacturing


Input material
ISRU process
Output material

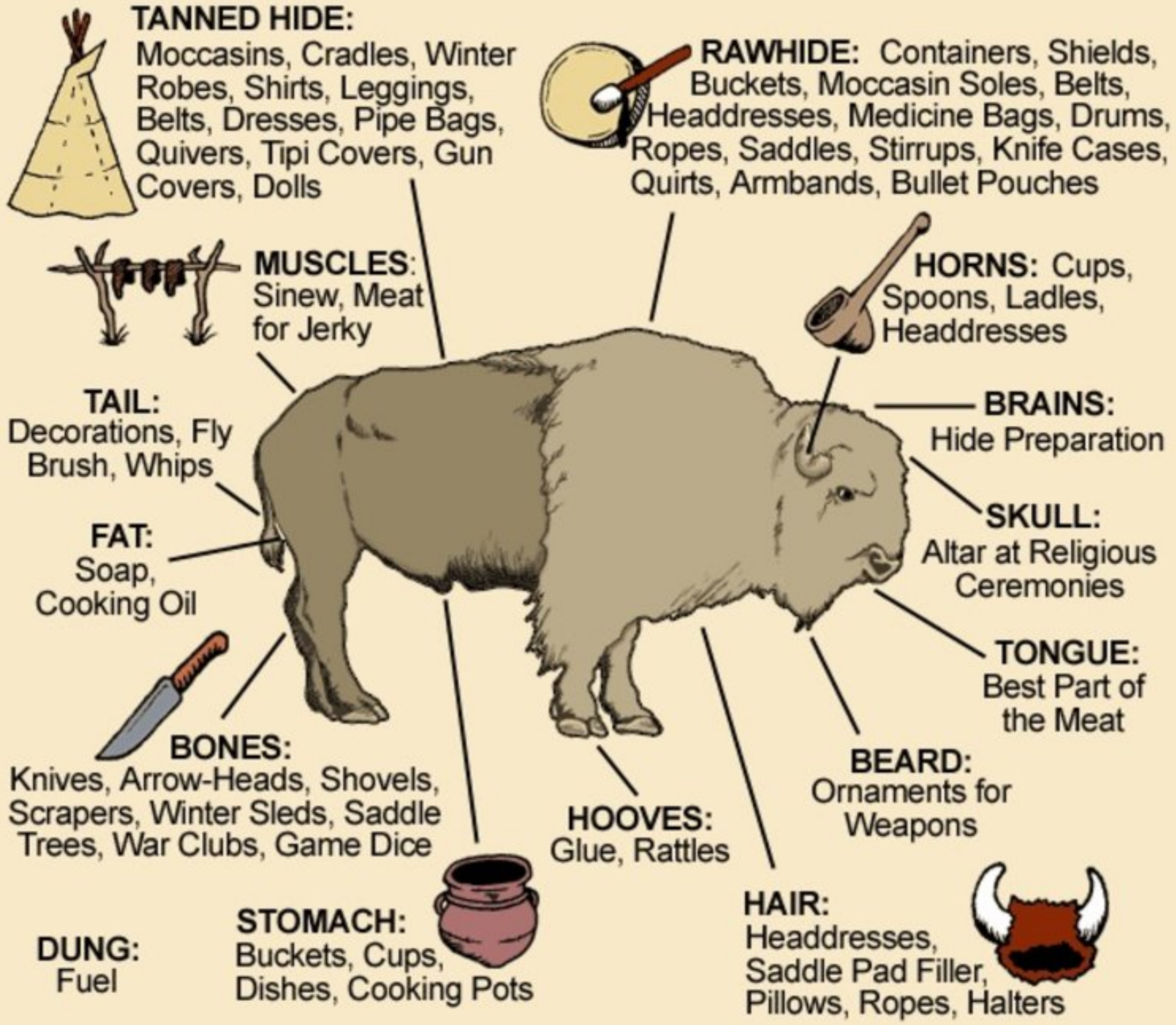

Bulk regolith
Filtering/
beneficiation
Filtered
input
Waste
ISRU process
Useful
output
Waste

Robert P. Mueller[1], Scott Howe[2*], Dennis Kochmann[3], Hisham Ali[4], Christian Andersen[5], Hayden Burgoyne[6], Wesley Chambers[7], Raymond Clinton[8], Xavier De Kestellier[9], Keye Ebelt[10], Shai Gerner[11], Douglas Hofmann[12], Kristina Hogstrom[13], Erika Ilves[14], Alex Jerves[15], Ryan Keenan[16], Jim Keravala[17], Behrokh Khoshnevis[18], Sungwoo Lim[19], Philip Metzger[20], Lucas Meza[21], Takashi Nakamura[22], Andrew Nelson[23], Harry Partridge[24], Donald Pettit[25], Rod Pyle[26], Eric Reiners[27], Andrew Shapiro[28], Russell Singer[29], Wei-Lin Tan[30], Noel Vazquez[31], Brian Wilcox[32], Alex Zelhofer[33]

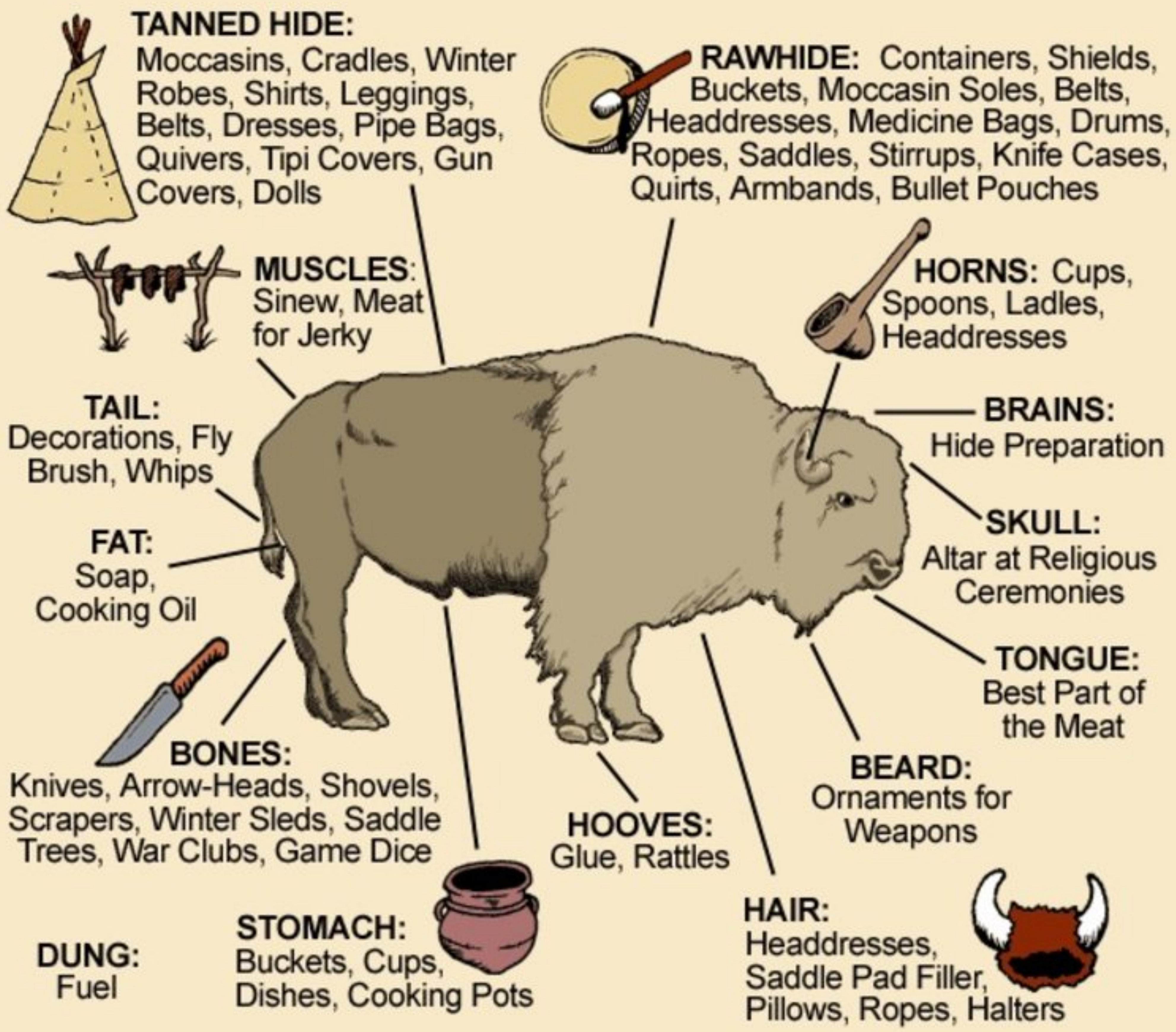
Table 3: Materials Processing with Lunar Resources

Label	Builds Upon	Additional Processes (cumulative with "builds upon")	Additional Materials Produced (cumulative with "builds upon")
1L	N/A	Sieve and/or grind regolith	Regolith
2L	1L	Molten Regolith Electrolysis	"Mongrel Alloy", Ceramic, Oxygen
3L	1L, 2L	Vacuum Distillation or equivalent	Elemental Aluminum, Iron, Magnesium, Calcium, Silicon, Titanium. (Also, if regolith obtained from KREEP terrane, then Potassium, Rare Earth Elements, and Phosphorus)
4L	1L-3L	Metals Refinery	Various alloys
5L	N/A	Ice Mining & Distillation	H_2O, CO, CO_2, NH_3, many compounds and trace metals
6L	5L	Fischer Tropsch process	CH_4, plastics, rubbers
7L	1L-6L	Metals Refinery including carbon from 5 & 6	Steel
8L	1L-3L	Slaking and cement production	Lime and cement
9L	1L-8L	Advanced processes	Most other materials

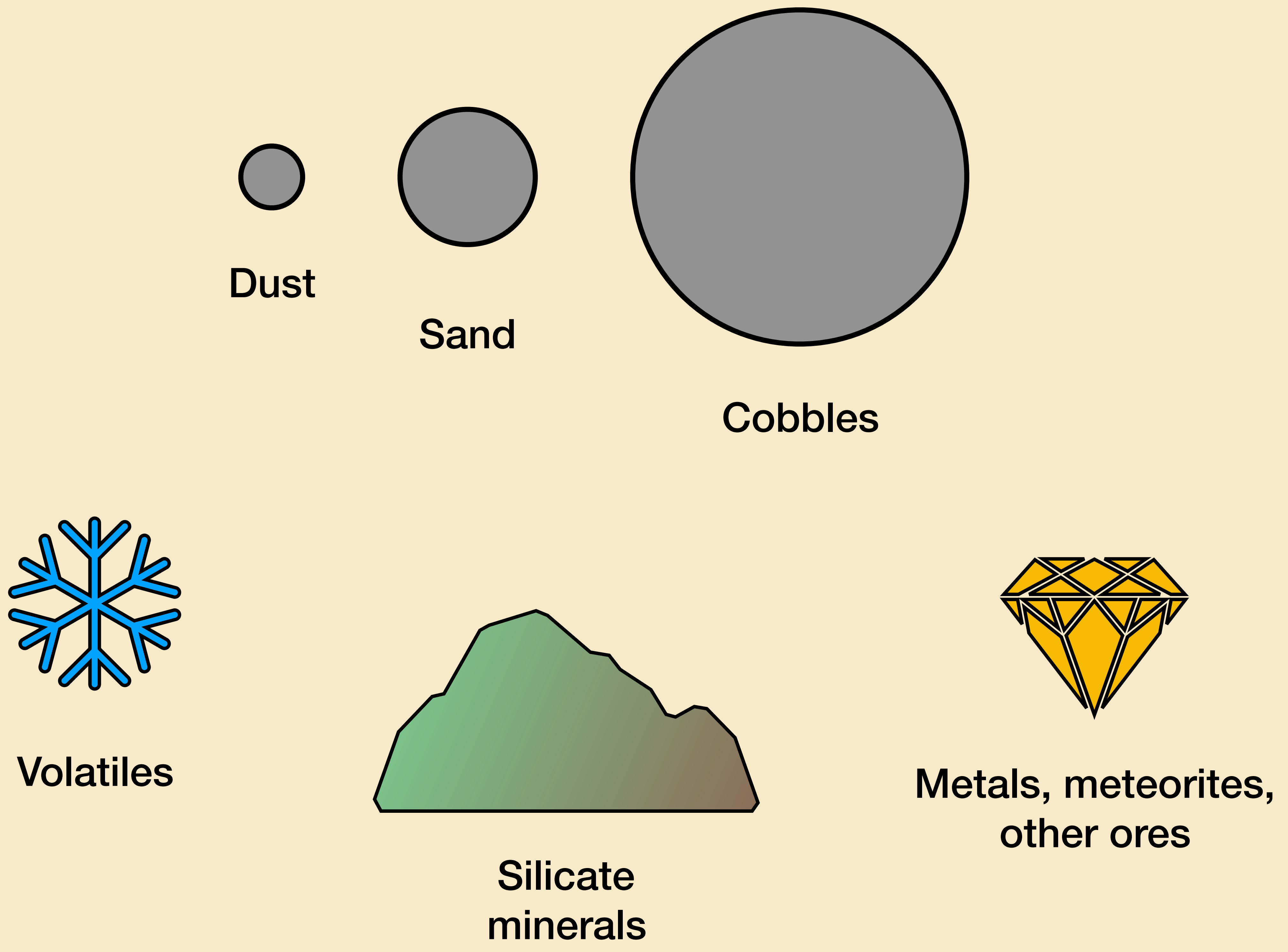
Using the "whole buffalo"



Using the "whole buffalo"



Using the "whole regolith"



Acta Astronautica

Available online 16 April 2019

In Press, Accepted Manuscript

ELSEVIER

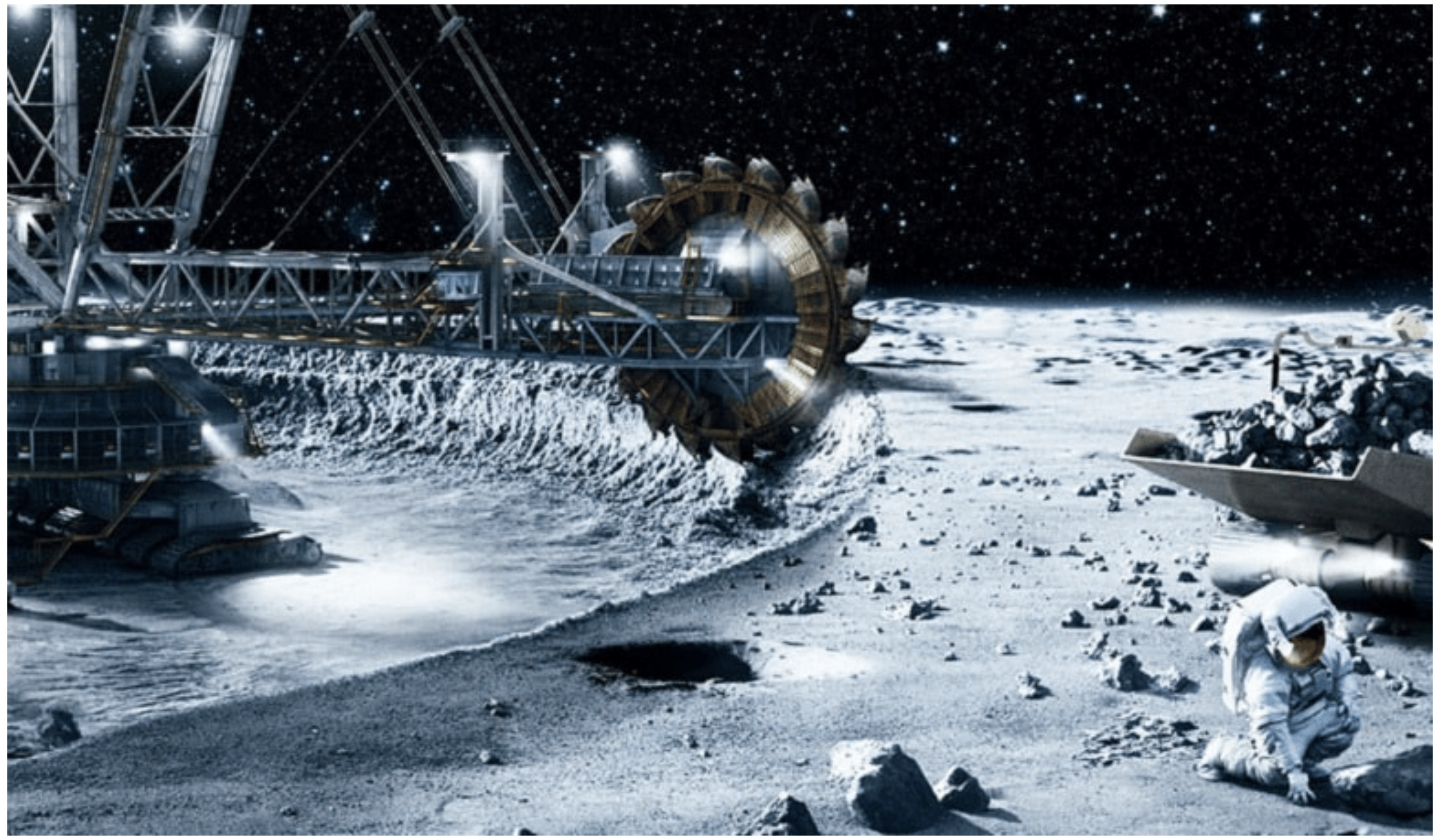
How much of the solar system should we leave as wilderness?

Martin Elvis [a], Tony Milligan [b]

Show more

https://doi.org/10.1016/j.actaastro.2019.03.014

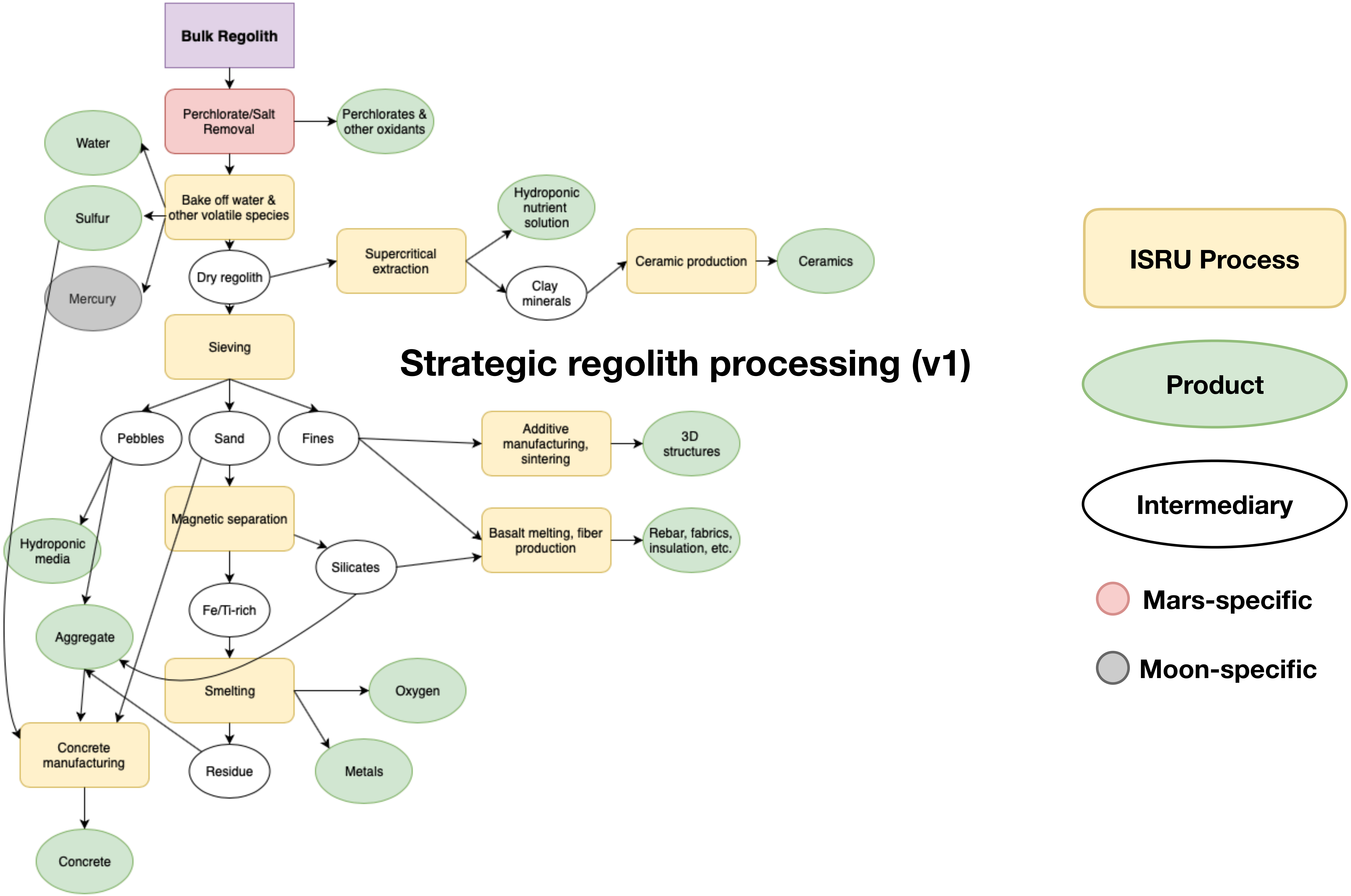
Get rights and content

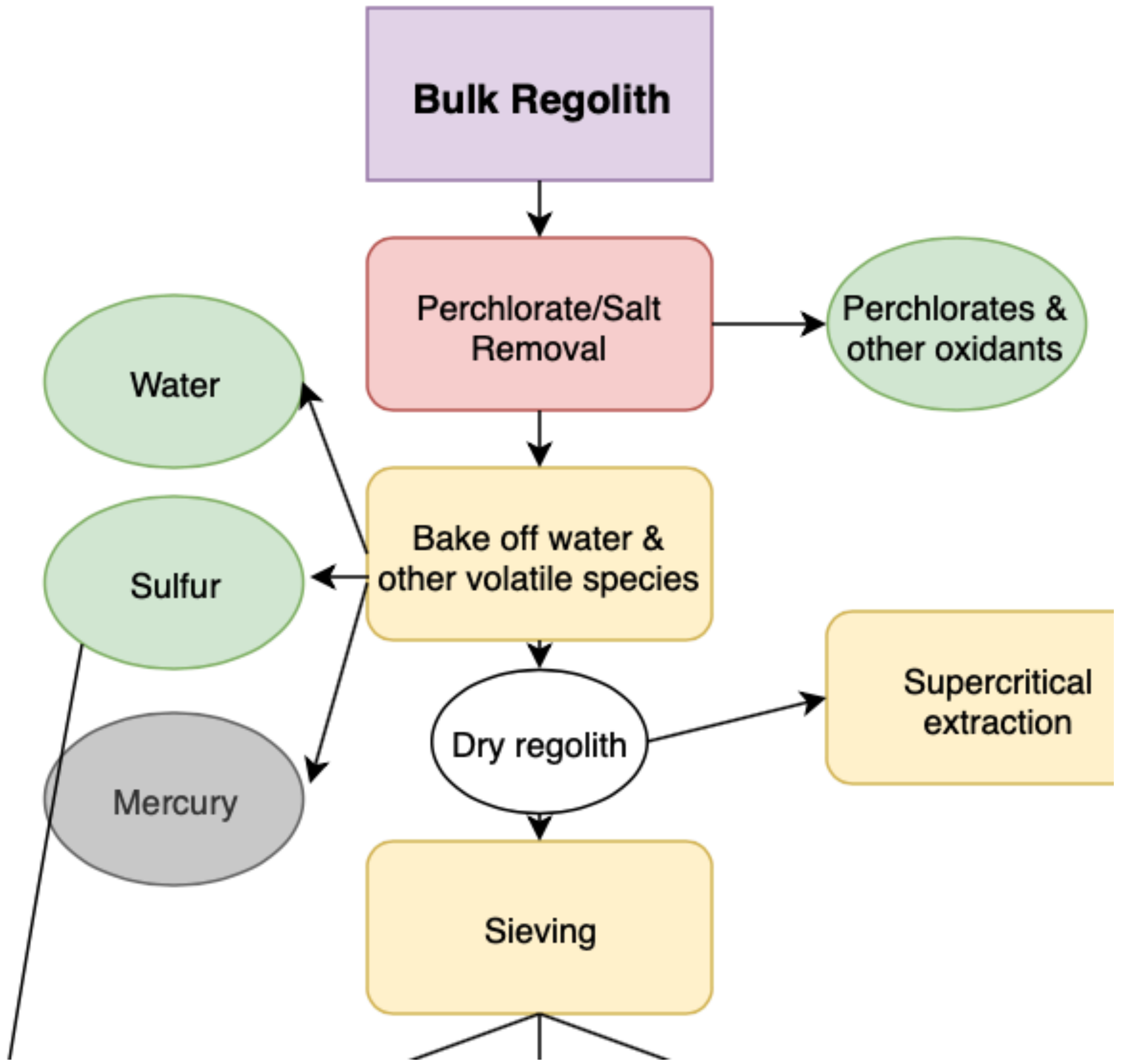


*“**we define the Circular Economy as** a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling.”*

– Geissdoerfer et al. 2017

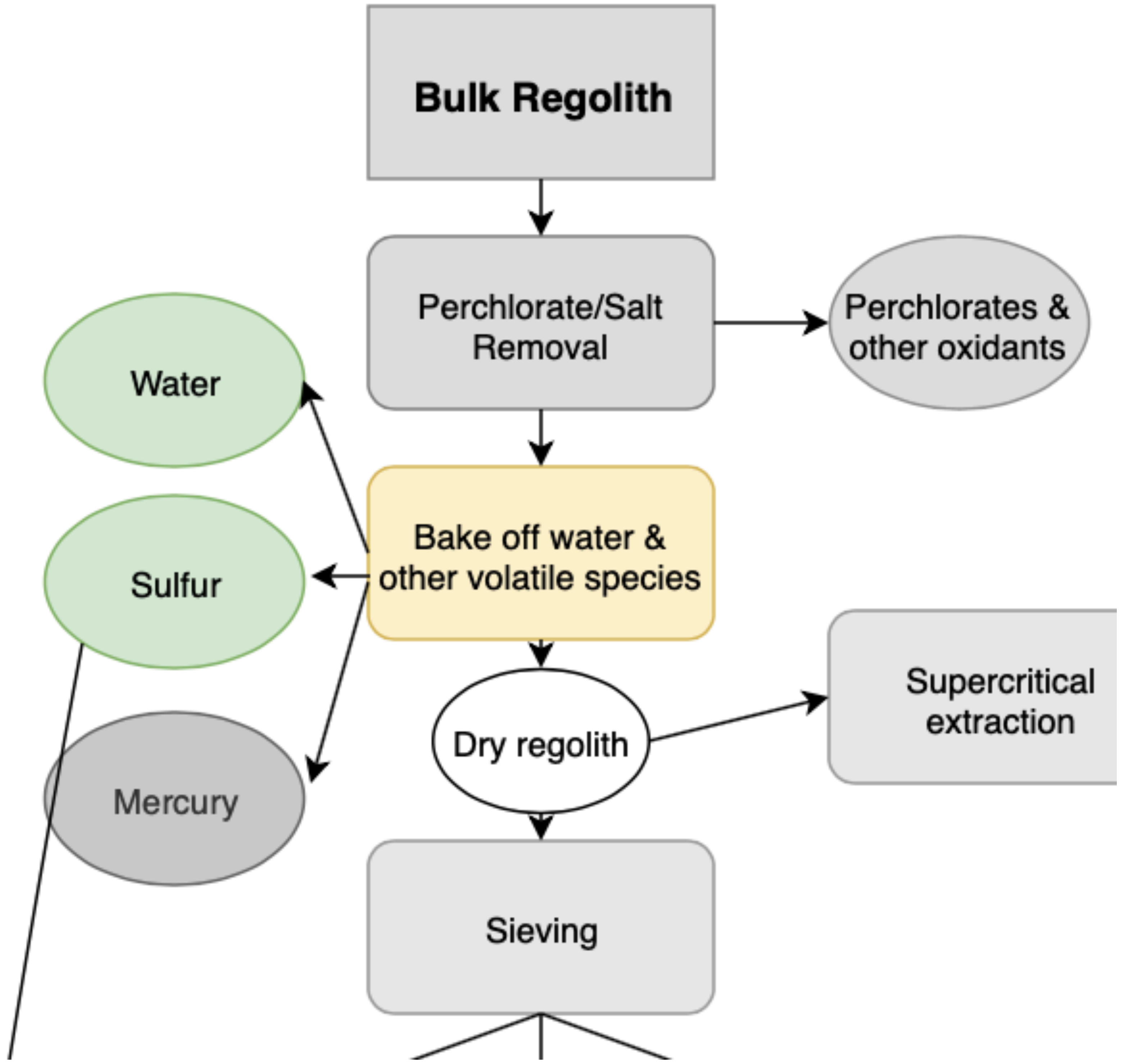
Strategic regolith processing (v1)

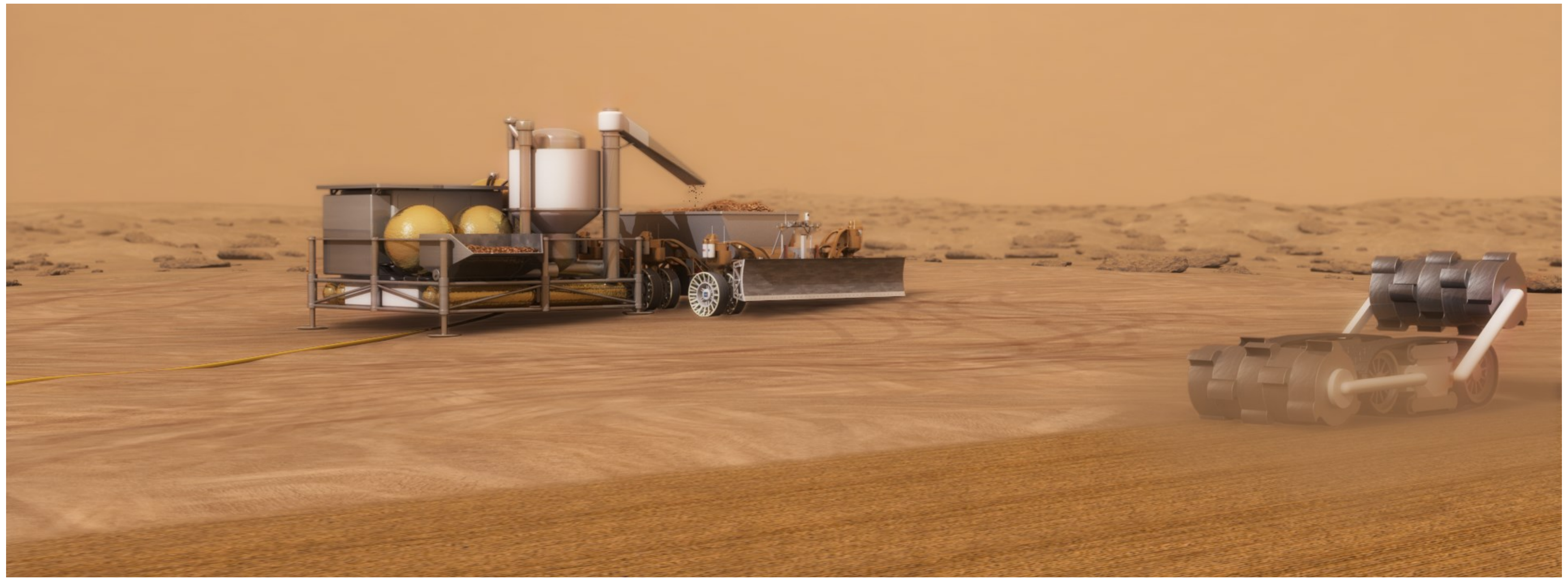




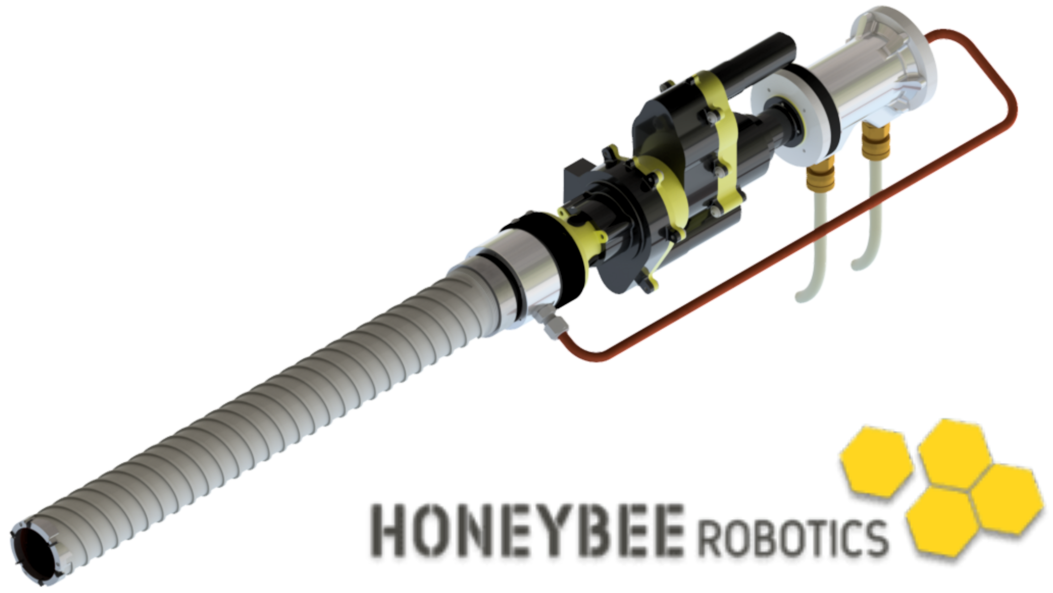
Volatile extraction

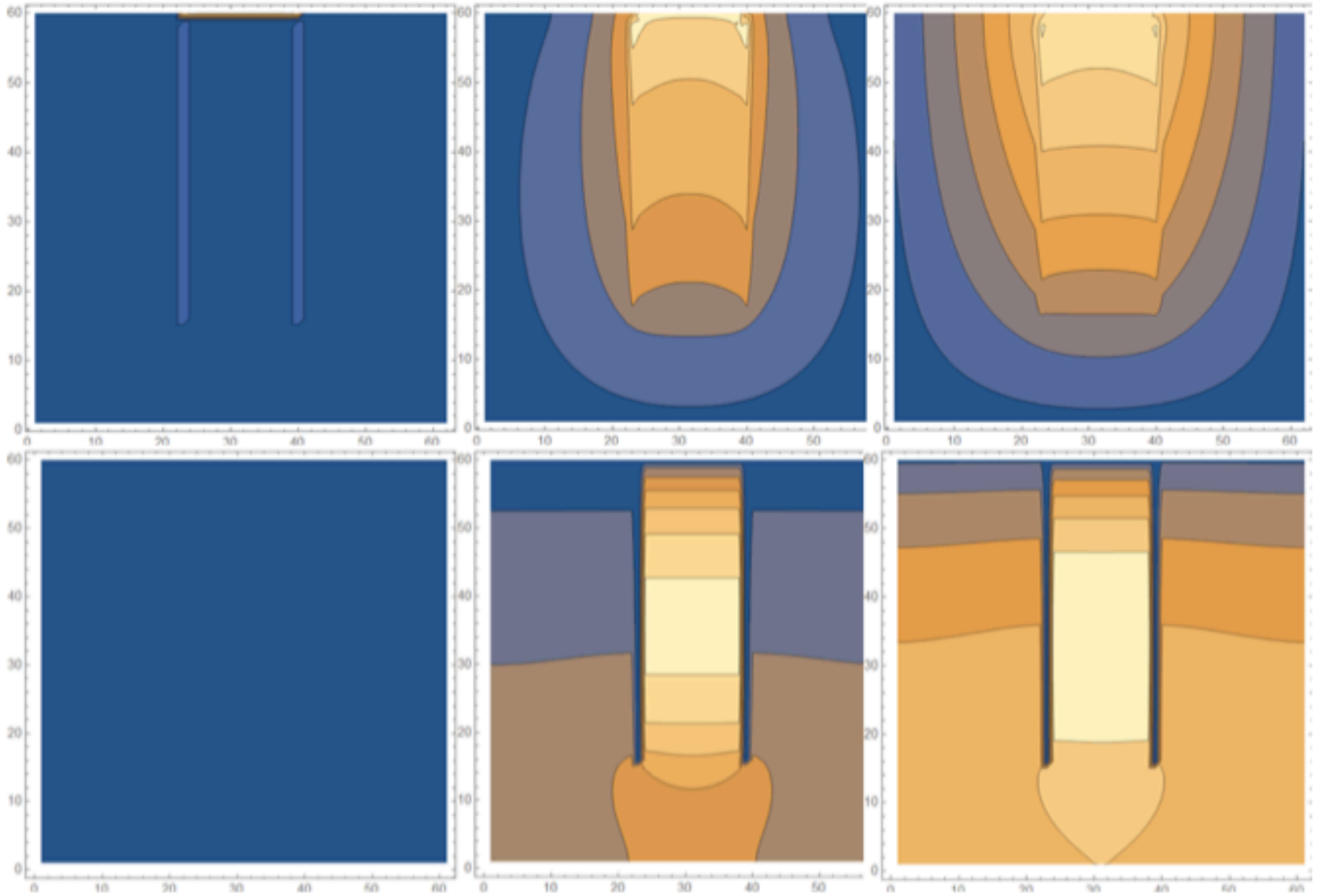
Species	Moon	Mars
H_2O/OH	Ice in PSRs, 1-5 wt.% with local enrichments 20% or higher. In pyroclastics at 100s ppm	Pure layers of ice at mid to high latitudes; high abundances in sulfates and clays
S	Various S-species at <1 wt.% in PSR material, minor sulfides in bulk regolith	Strata enriched in sulfate phases, scattered throughout equatorial regions and in polar dunes
C	Some minor C-bearing phases in PSR material	Sparse carbonate minerals, ppb levels of organics in some strata
ClO_x	[redacted]	Perchlorate and/or chlorate salts in some strata 1-2 wt.%
N	[redacted]	Nitrates at up to wt.% levels in some strata
He	^{3}He at ppb levels in regolith	[redacted]
Hg	Detected by LCROSS in PSR material	[redacted]

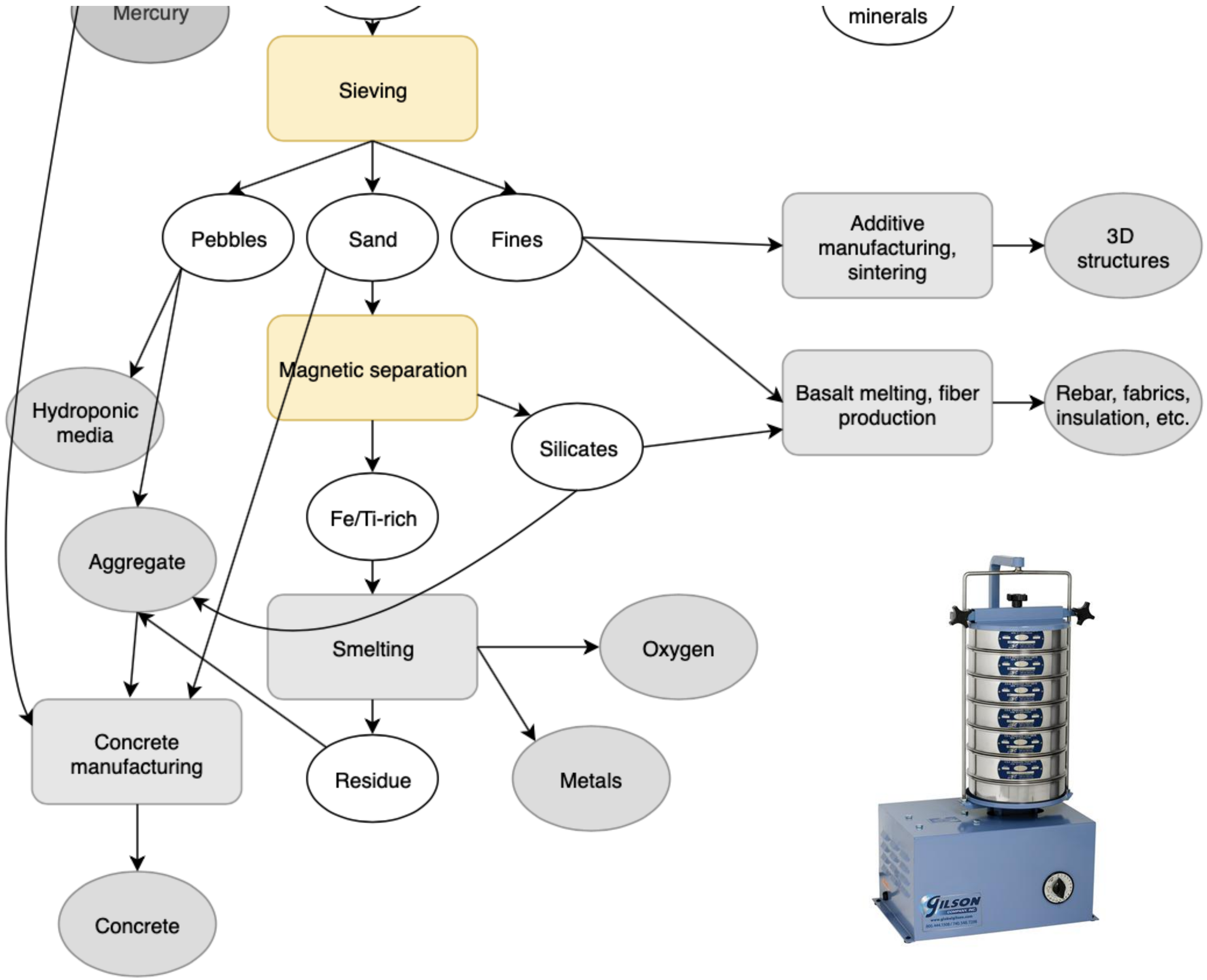




Volatile extraction



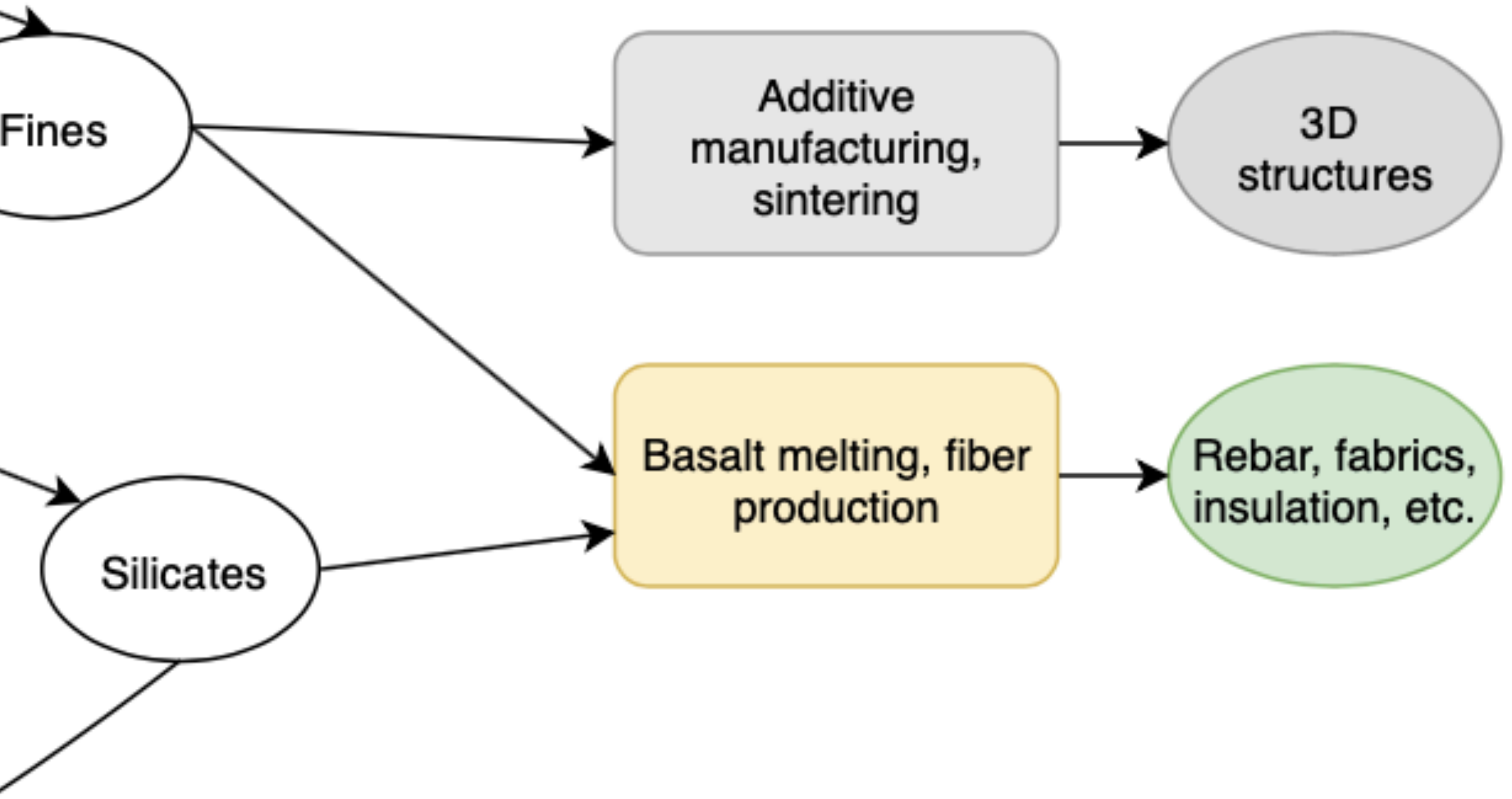




(12) **United States Patent**
Walton et al.

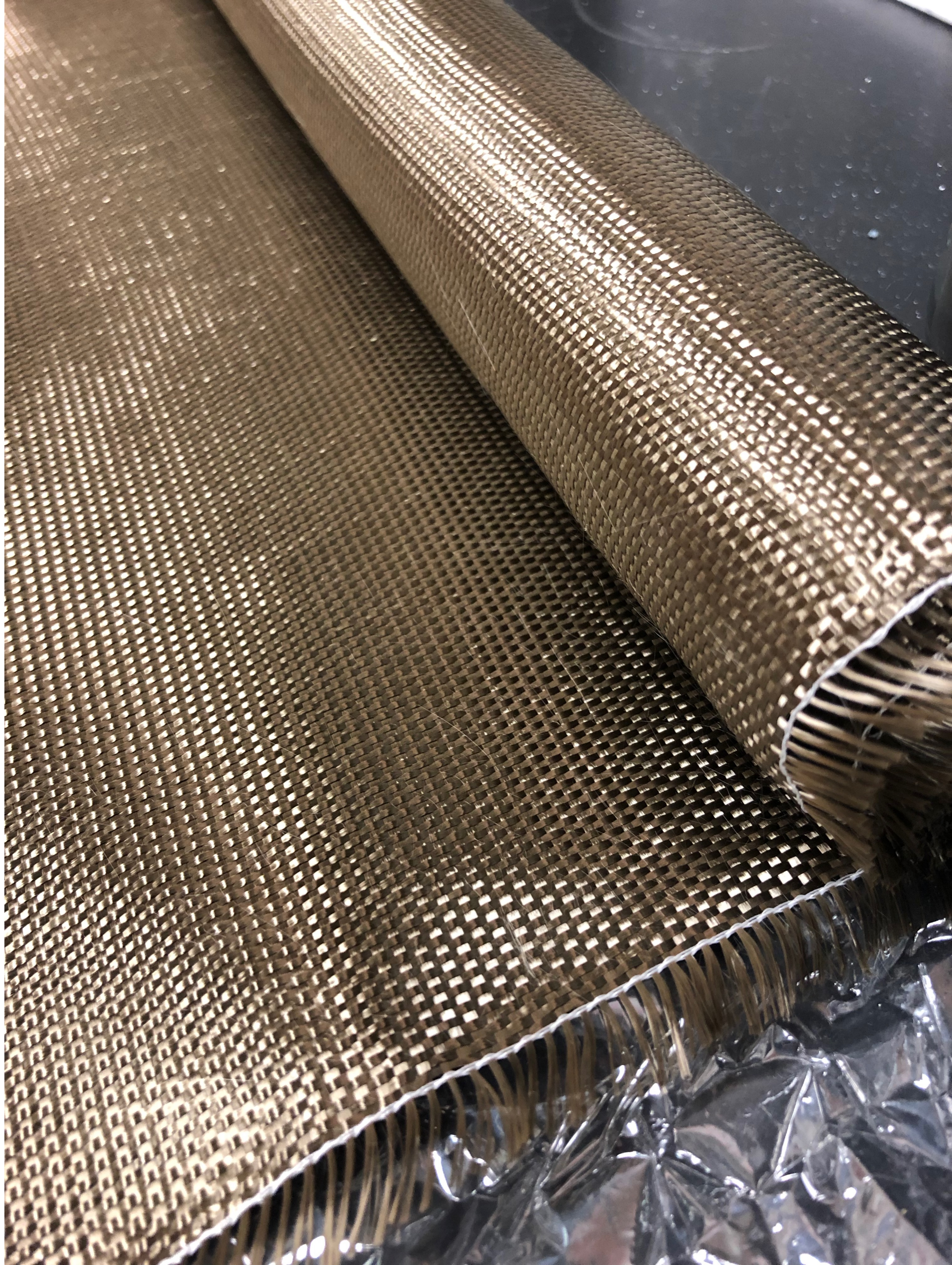
(54) **CENTRIFUGAL SIZE-SEPARATION SIEVE FOR GRANULAR MATERIALS**

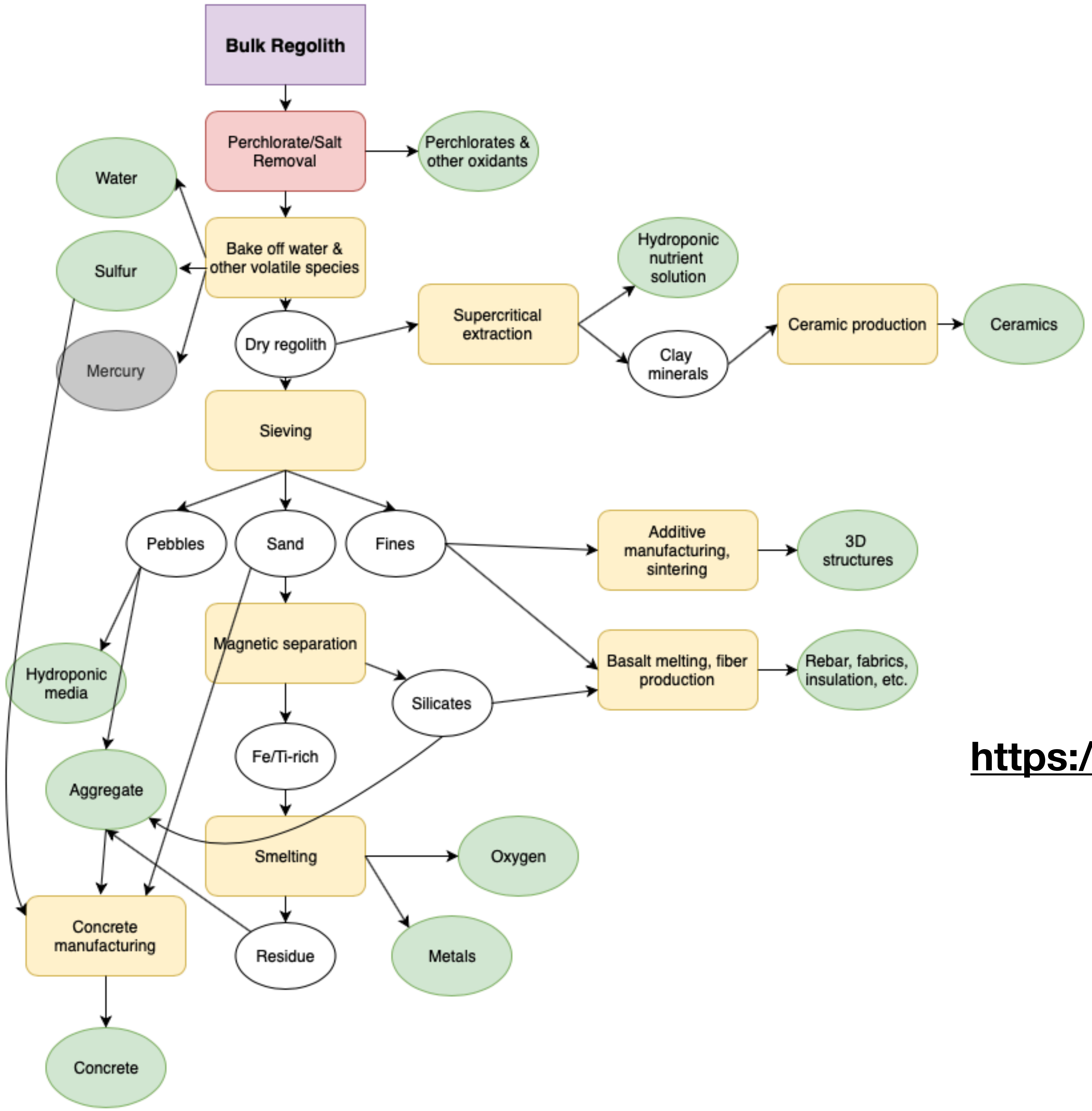
(76) Inventors: **Otis Walton**, Livermore, CA (US); **Christopher Dreyer**, Lakewood, CO (US); **Edward Riedel**, Boulder, CO (US)


Fines
Additive manufacturing, sintering
3D structures
Basalt melting, fiber production
Rebar, fabrics, insulation, etc.
Silicates


MADE OF MARS

mafic™





draw.io

https://kevincannon.rocks/StrategicRegolithProcessing.xml

EXOLITH
LAB

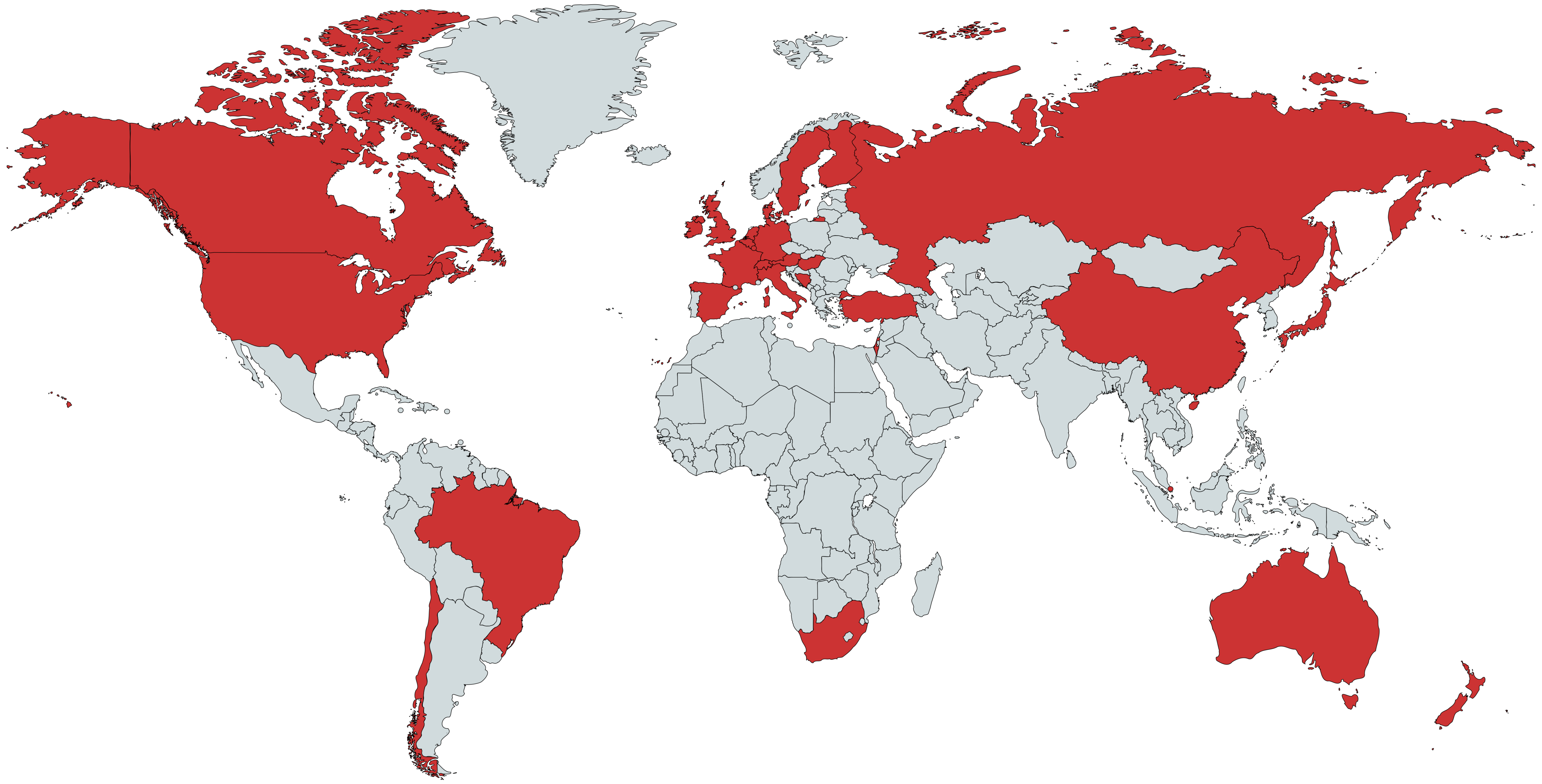
https://sciences.ucf.edu/class/exolithlab/

EXOLITH LAB

https://sciences.ucf.edu/class/exolithlab/

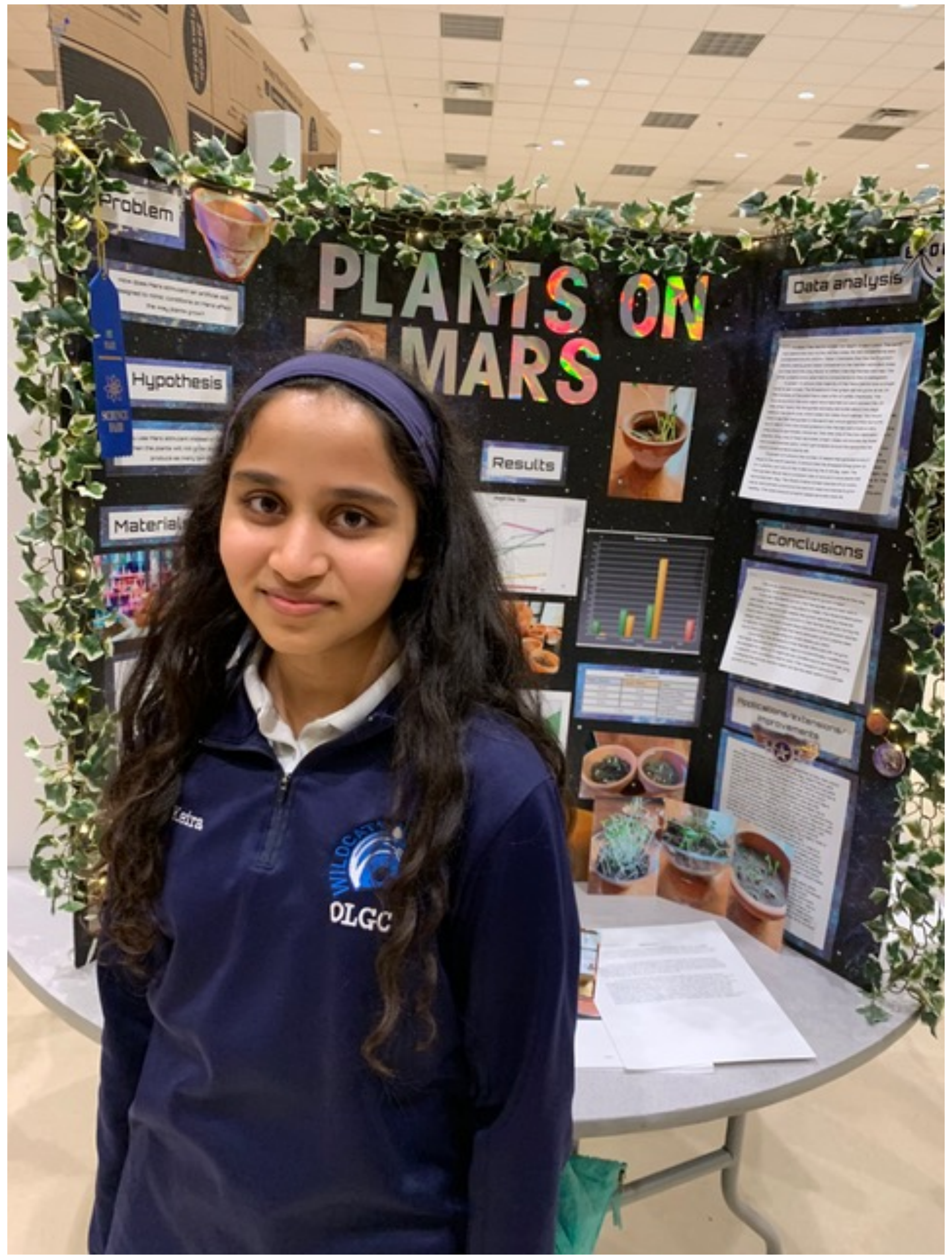
Currently: **1581 kg** of simulants delivered to **275 customers** in **30 countries**

>160 different research projects



EXOLITH LAB

https://sciences.ucf.edu/class/exolithlab/



COLORADO SCHOOL OF MINES

Florida Institute of Technology

NanoSonic
Putting nanotechnology to work

NASA

TRANS ASTRA

UC San Diego

LSU
LOUISIANA STATE UNIVERSITY

https://kevincannon.rocks/LunarIceProspecting_v1.0.pdf

Freely available white paper on ice prospecting.

Covers:
- Synthesis of orbital datasets
- Likely physical properties of deposits
- Operability considerations

Will be updated in the future as new data comes in.

Concluding thoughts:

- **Regolith-based ISRU can be treated as linked chains instead of isolated processes**
- **It’s not too soon for thinking about sustainability: build it in from the start**
- **There are many creative uses for different regolith components, more than mentioned here**
- **Many of these can be tested with simulants, but we can’t do it all alone**