Exploration, Conveying, Mining Cycles and Mining Requirements

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NASA SSERVI, UCF
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ASCE | AEROSPACE

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Introduction

- Exploration
- Conveyance
- Mining Requirements
- Mining Cycles

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Exploration

- **Find resource location, geometry, quantity and properties**
- **Identify physical property and geological setting to detect**
- Location (Earth, Moon, Mars, Asteroids, etc.)
  - Remote (telescope)
  - Orbital
  - Aerial
  - Ground
  - Drill
- Sensing Method
  - Passive Imaging (varying wavelengths, radio to gamma)
  - Active Imaging (varying wavelengths, radio to gamma)
    - Absorption, reflection or diffraction
    - Direct imaging or spectroscopy
  - Gravity (deep but low resolution)
  - Magnetism (shallow, but higher resolution than gravity)
  - Conductivity (electro magnetic)
  - Seismic (acoustic)

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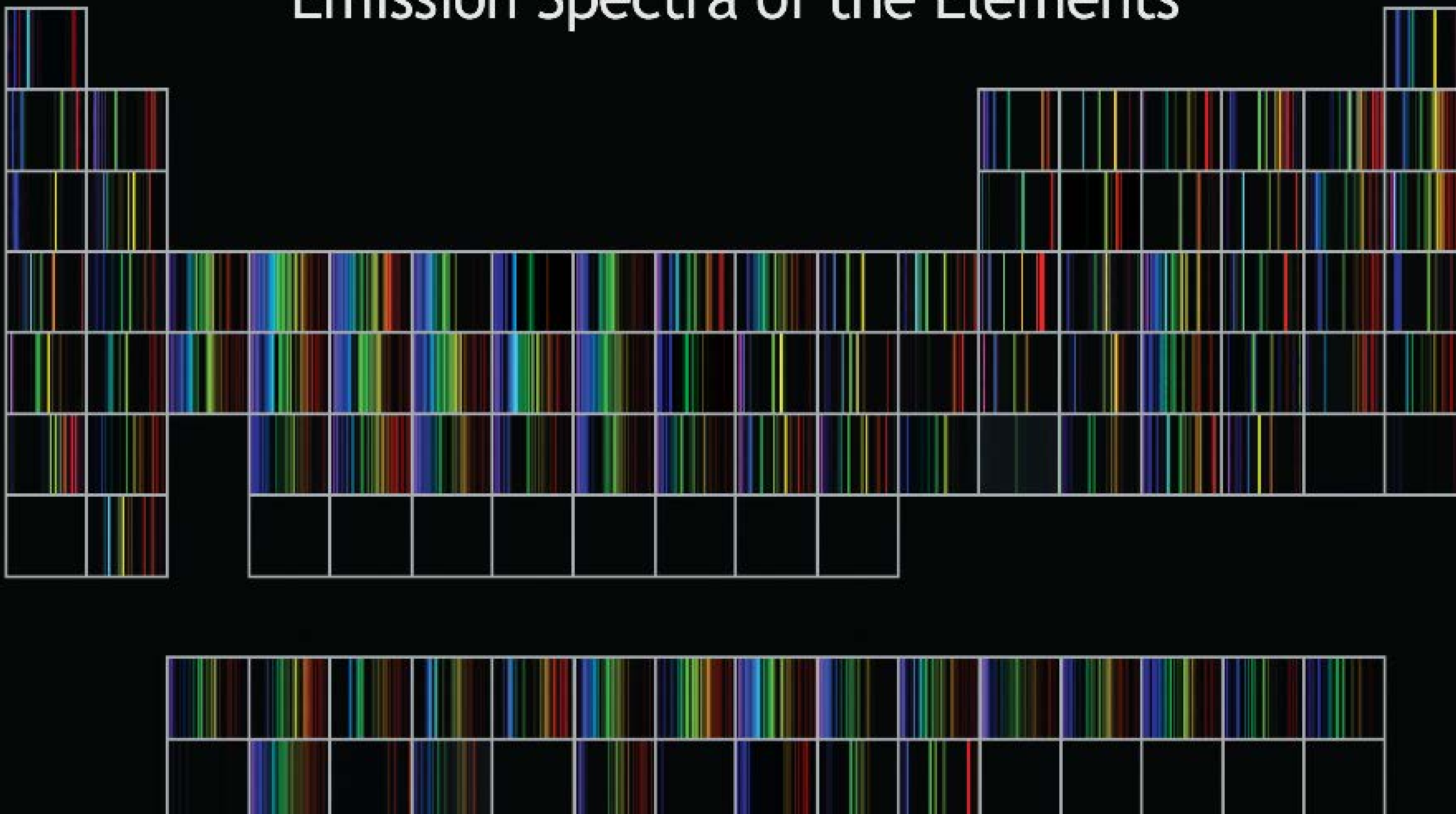
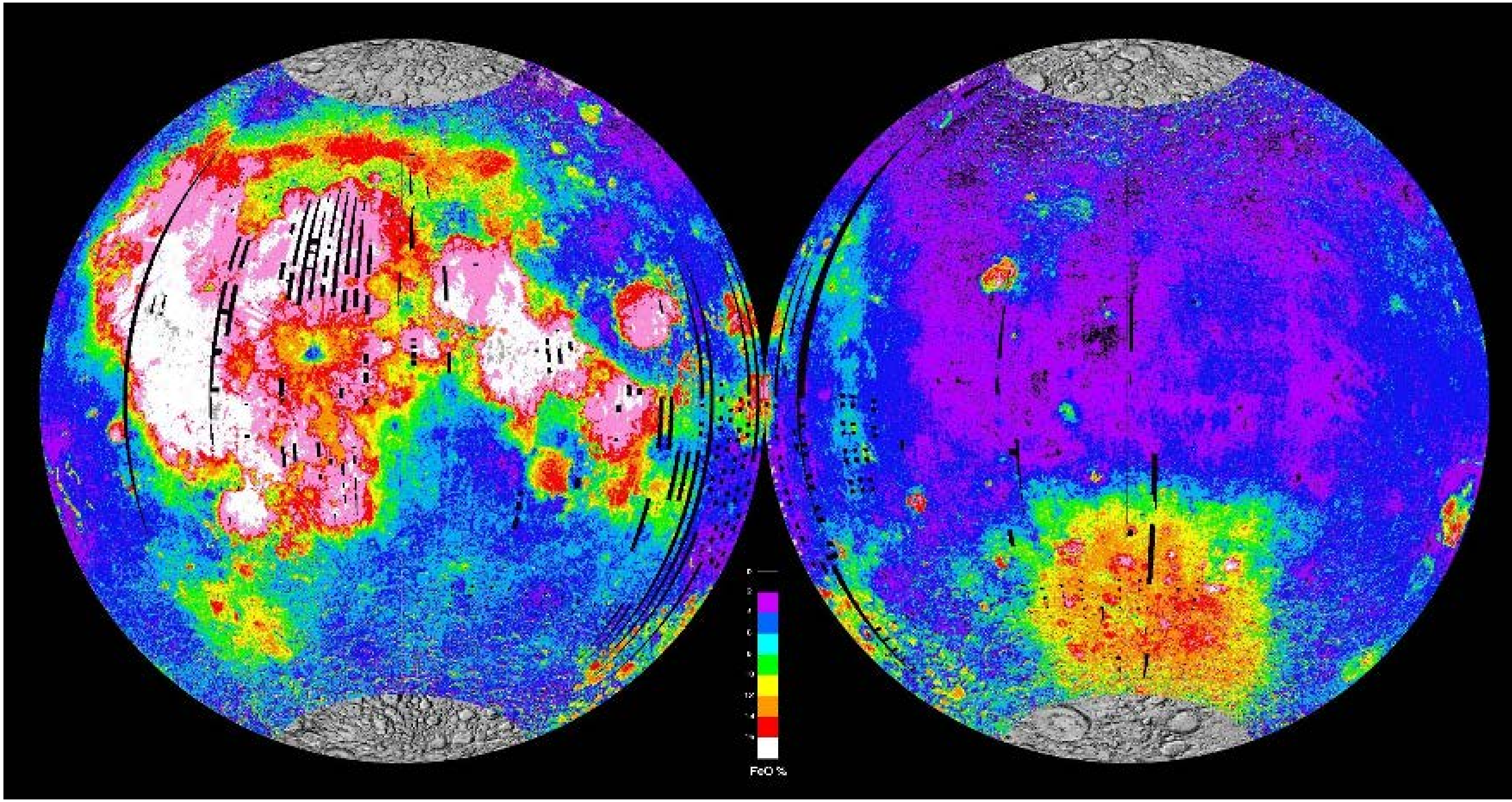
Emission Spectra of the Elements



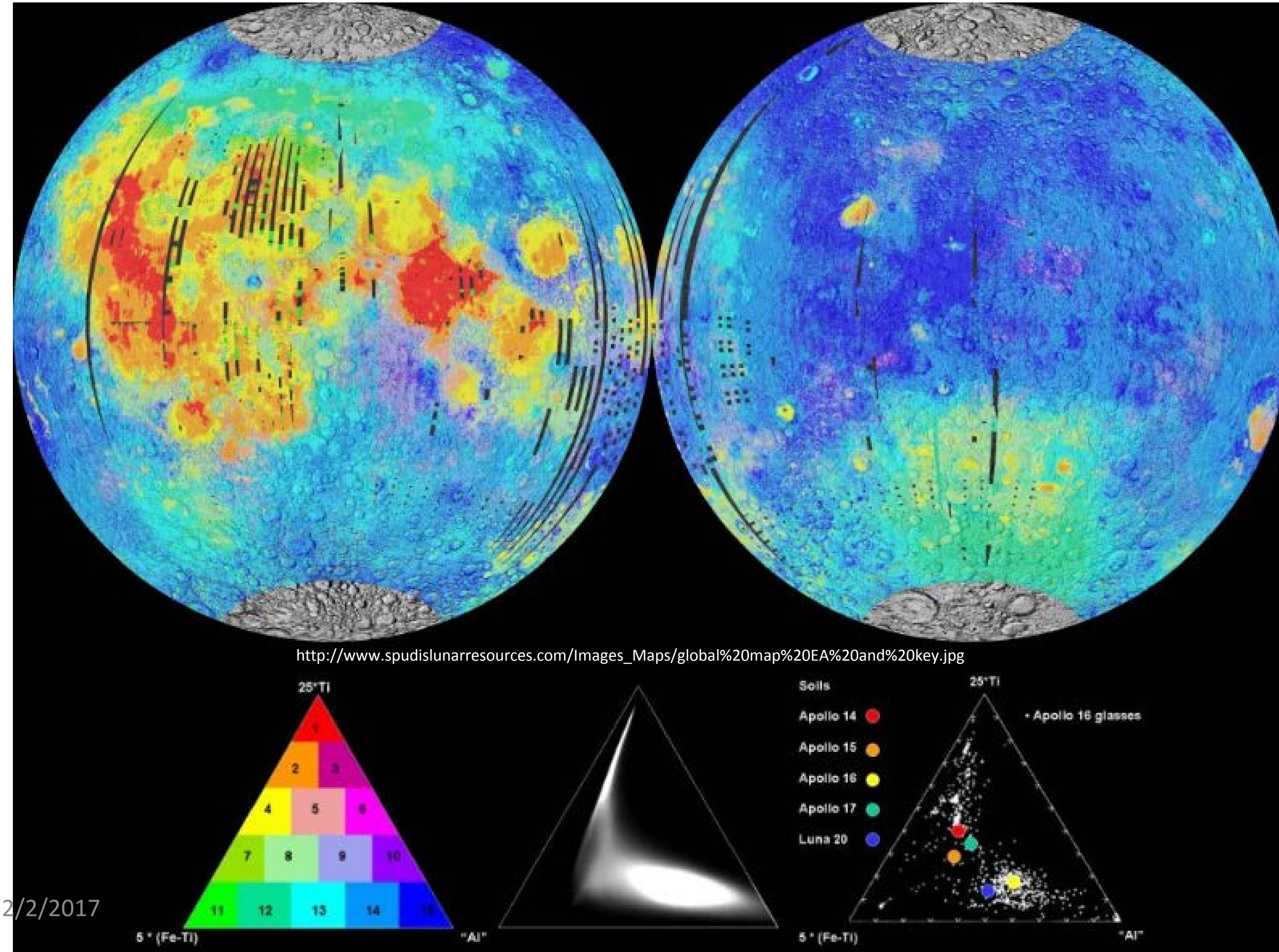
field·tested·systems
REAL-TIME CLASSROOM SPECTROSCOPY

Moon, FeO

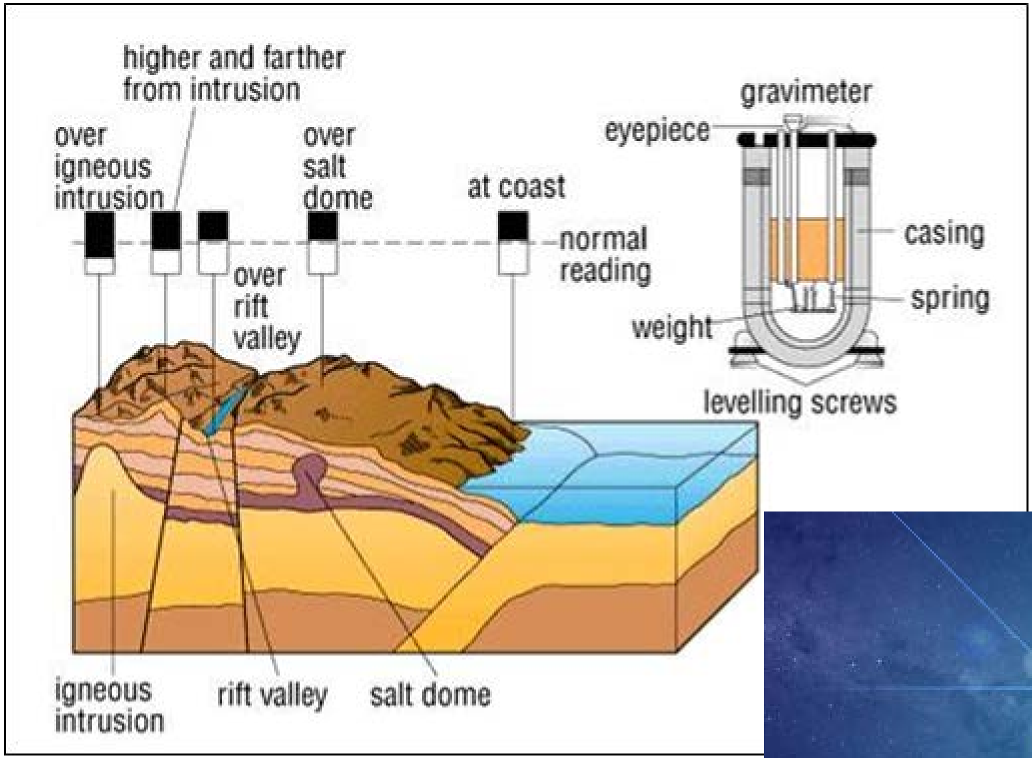


http://www.spudislunarresources.com/Images_Maps/global%20Fe%20EA.jpg

Moon, Mineral identification

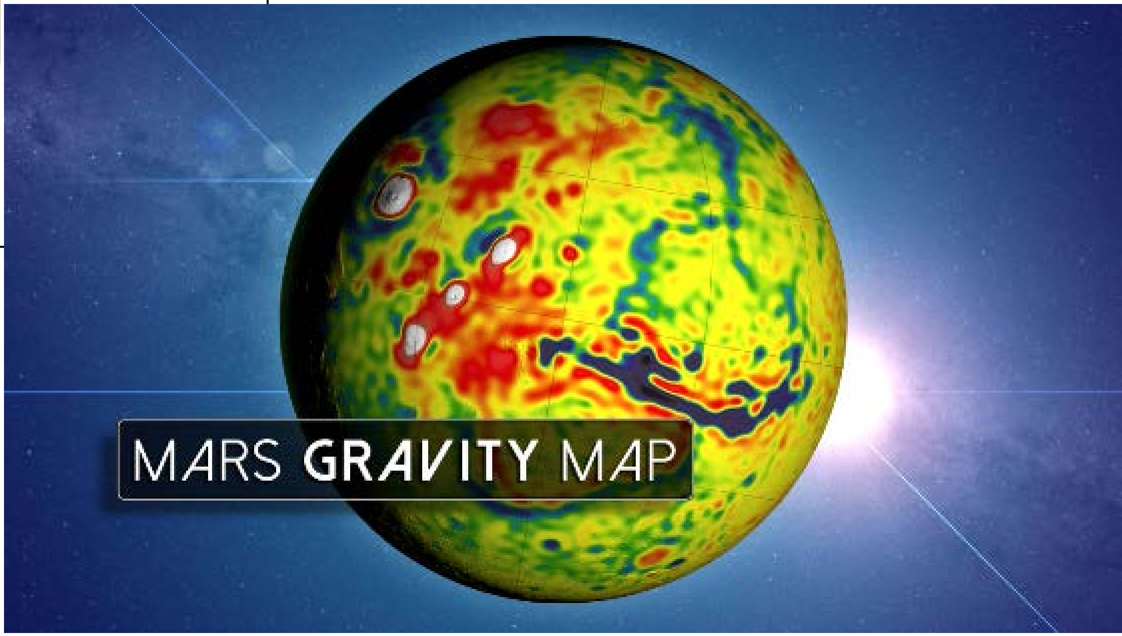


Gravity Methods



http://www.eo-miners.eu/earth_observation/eo_eof_eom_geophysical.htm

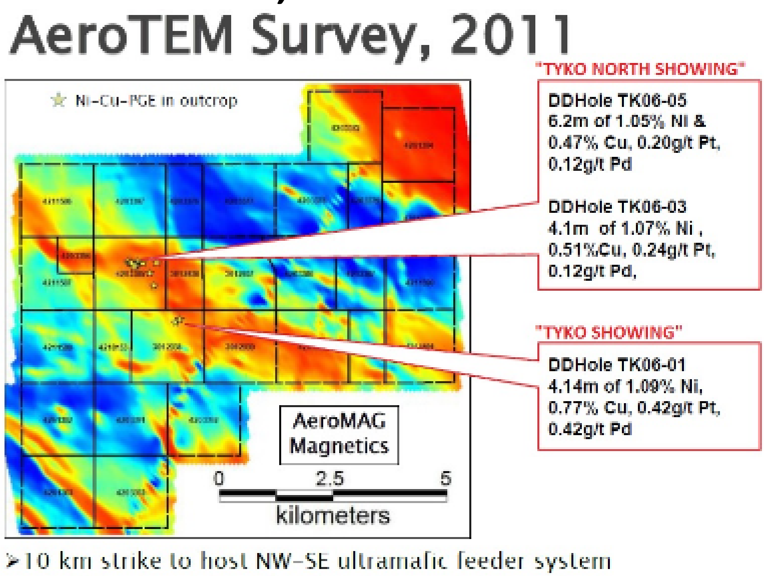
- Gravimeter
- Local or global level
- Depends on density



http://svs.gsfc.nasa.gov/vis/a000000/a004400/a004436/MarsGravityMapYouTube.jpg

Magnetometer

- Uses a magnetic dipole
- Induces a magnetic field, measure resultant, can deduce remnant magnetic field present
- 3 rock type identification
  - Diamagnetic
  - Paramagnetic
  - Ferromagnetic (has 3 types also)



- Stay within 10-15 km of base station
- Eliminate internal and external magnetic field, want anomalies

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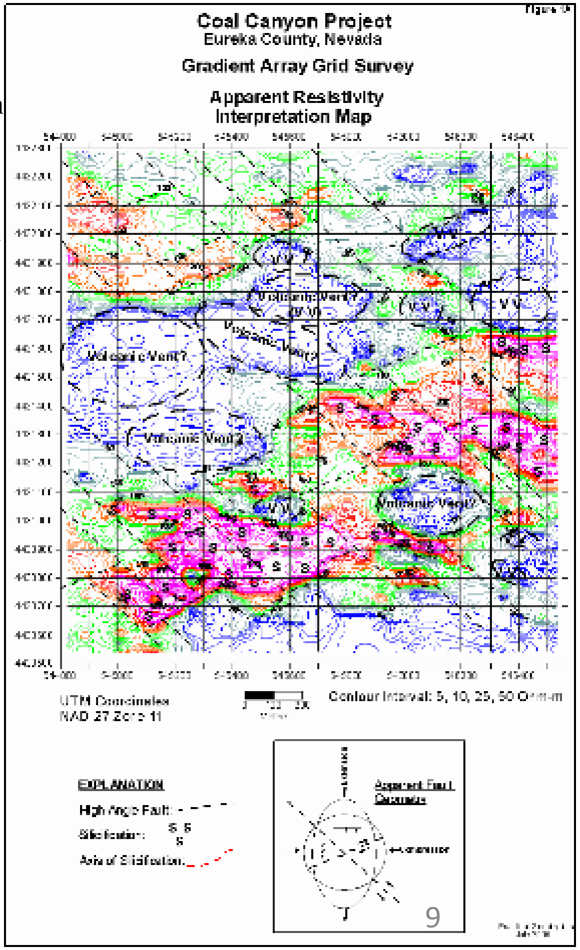
Electromagnetics

- 4 methods: spontaneous polarization, induced polarity, phase induced polarity, complex resistivity (spectral induced polarity)
- When using two electrodes connected to ground they give you a difference in potential
- Requires good contact with ground
- Uses 100-200 mV
- Several methods (patterns) exist
- **For shallow targets 3-50 m depth**
- **Use 3-5-10m spacing**
- Can be used in boreholes also

a gradient array resistivity survey (GAR and a spontaneous potential gradient survey (SPG) over an area of approximately 1.75 by 1.75 miles. GAR is a well-established method for detecting and delineating alteration zones, in particular silicification, as well as high angle fault zones. Effective search depth is 1,000 feet. SPG, on the other hand, detects oxidizing, vertically extensive sulphide mineralization. A summary of the GAR and SPG data is shown in the figure to the right:

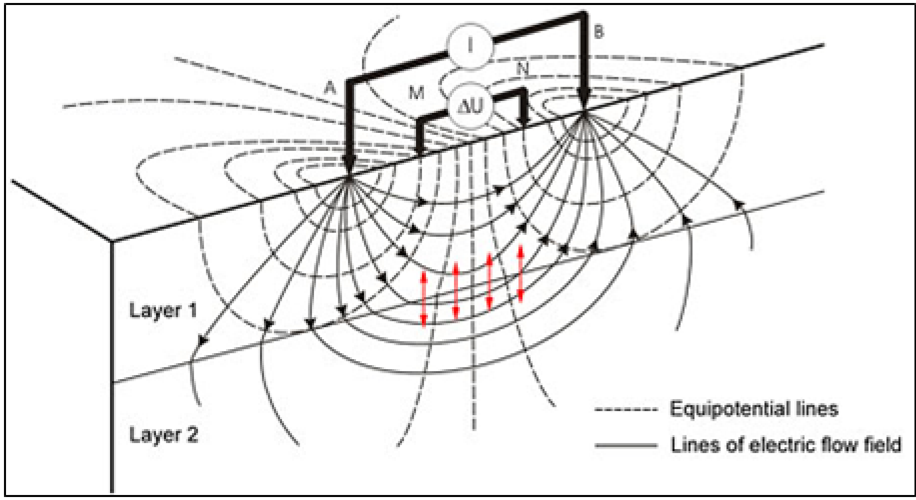
- Electric resistivity / conductivity can vary 20 orders of magnitude
- Three ways
  - Electric (Ohmic) – free electron movements (small amounts)
  - Electrolytic (current carried by ions) – predominantly used
  - Dielectric conductions – slight rotation of atoms (for radar)
- **Water, salinity, temperature, water distribution play large roles**
- Depth of discovery is prop. to distance between farthest active electrodes
- Dipole-dipole method only for profiling
- Schlumberger method for sounding & profiling



https://www.sec.gov/Archives/edgar/data/1346022/000113707006000009/ex105coalcanyon.htm

Natural and uniform field methods

- Telluric method
  - Only works with highly resistive (insulating) base layer
- Magneto telluric method
  - Gives best results over uniform, isotropic, horizontal beds in which resistivity only varies with depth
  - Base station can be setup to improve s/n ratio



- Artificial fields (loop loop fields, two loops oriented in many ways)
  - **Typically 50-800 ft distance between loops**
  - Stations measure at ½ the interval
  - **Max theoretical depth is ½ the spacing**
  - 2-4 miles a day coverage, 2-3 min per measurement
  - Designed to detect dikes/conductors

Seismic Methods

- Refraction and Reflection methods
- Body waves
  - P-wave (particle motion // to wave propagation)
  - S-wave (particle motion perpendicular to wave prop)
- Surface waves
  - Love waves (particle motion perp to prop on surface)
  - Rayleigh waves (particle motion elliptical retrodirection in the vertical plane)
- Refraction Method
- Reflection Method

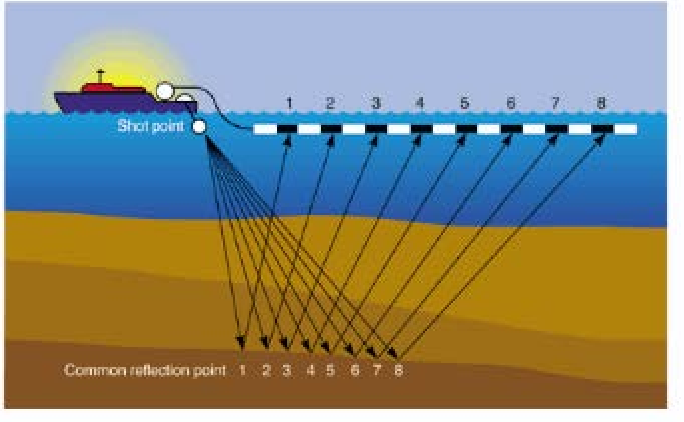


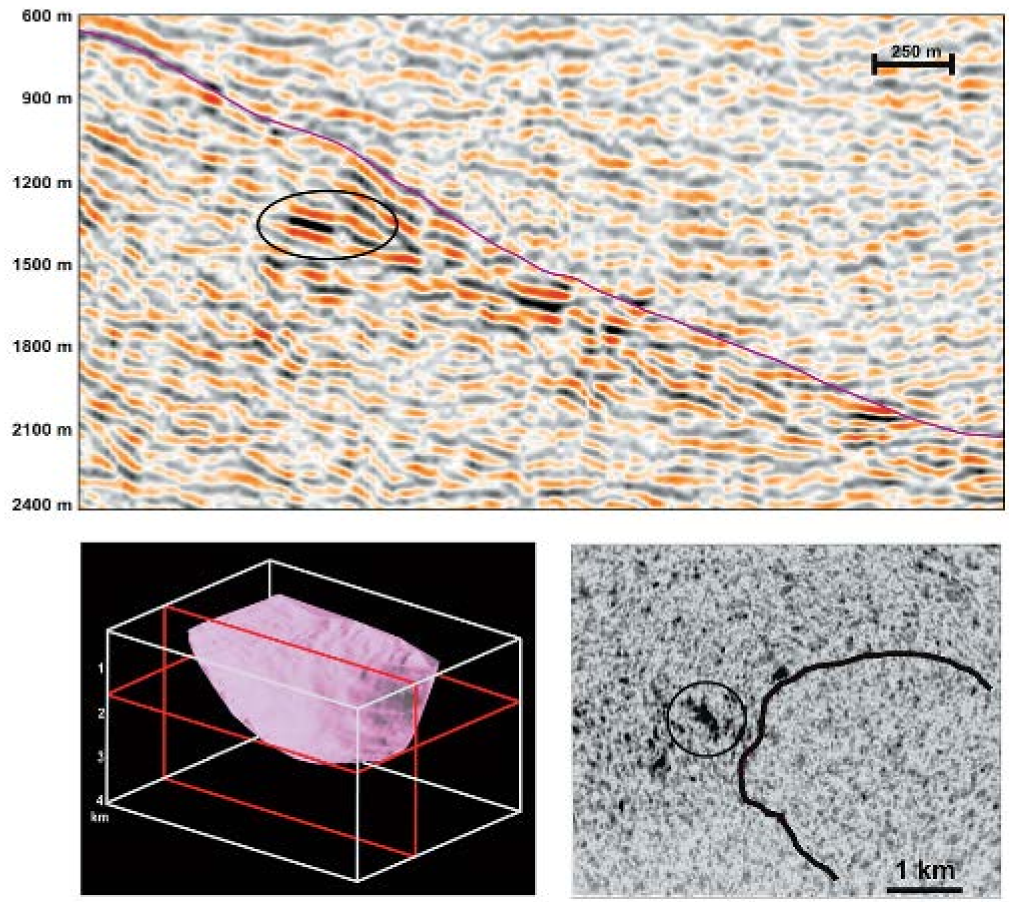
Figure 4. Underwater explosions are set off to generate acoustic waves that reflect off geologic layers and are received by a linear array of equally spaced hydrophones.

https://str.llnl.gov/str/Clark.html

Most often for large scale bodies

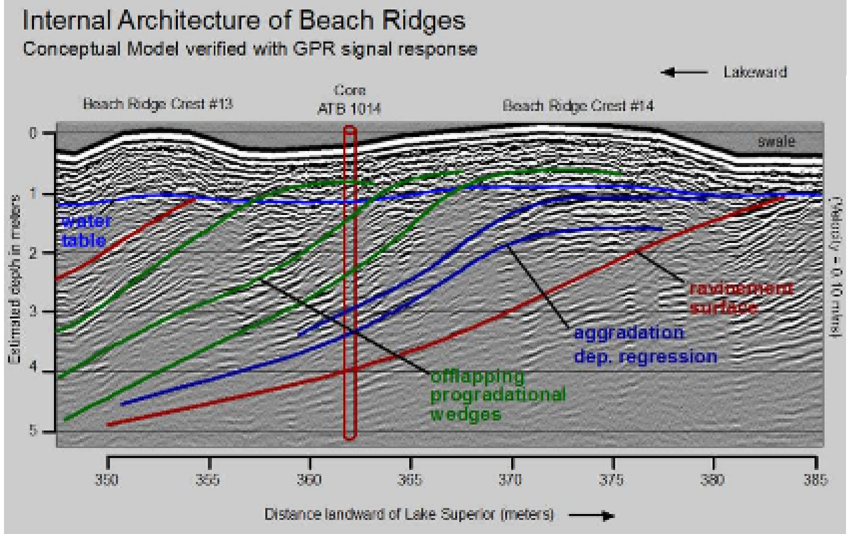
3D seismic survey at Sudbury: vertical section and interpreted SIC/foot - wall contact (top), 3D view of the dipping contact (lower left), red lines show the locations of the depth section and time slice (bottom right). Bright spots corresponding to possible sulfide deposits can be seen on both seismic sections.

<u>Km scale</u>

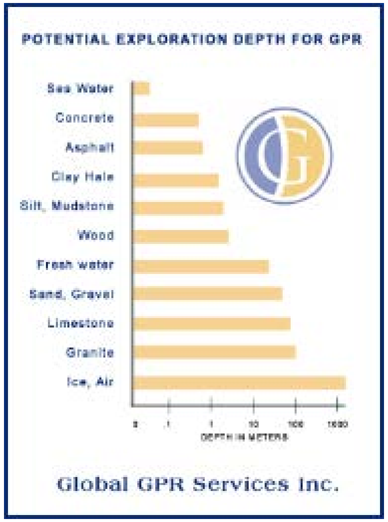


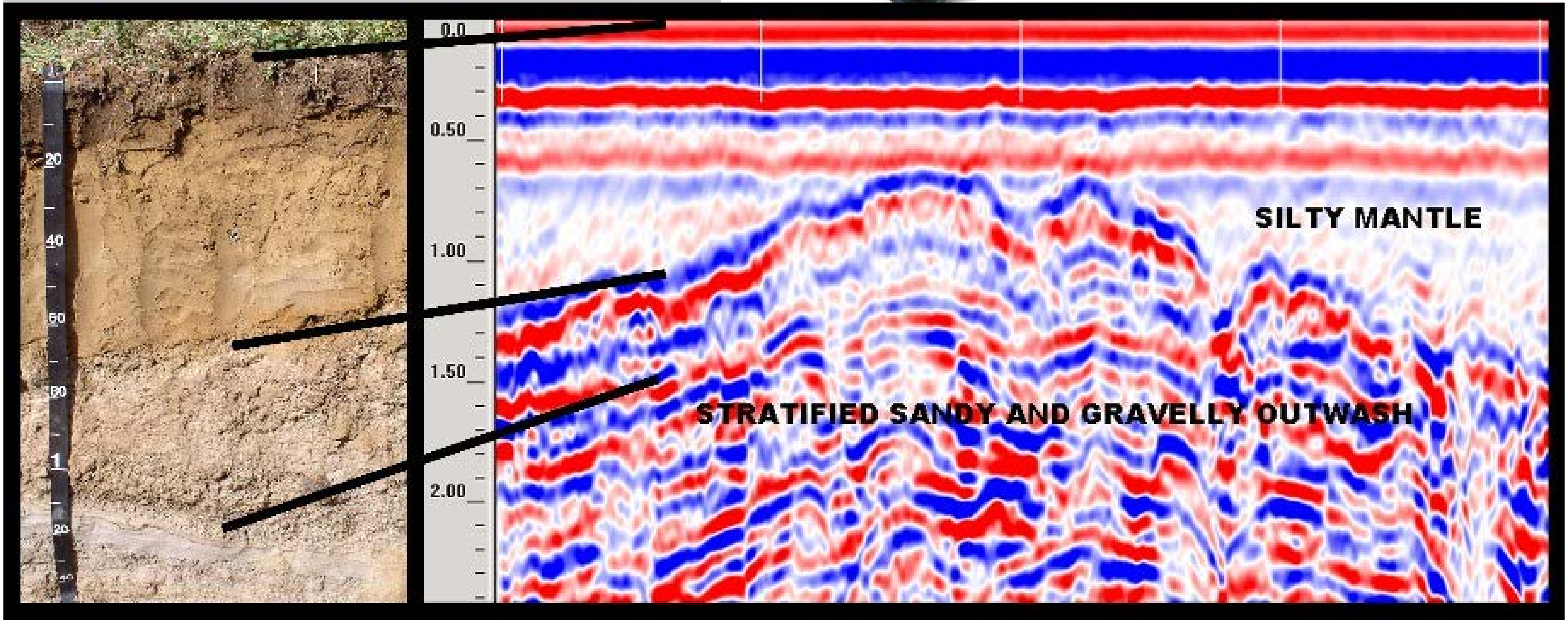
http://csegrecorder.com/articles/view/3d-seismic-exploration-for-mineral-deposits-in-hardrock-environments

Ground Penetrating Radar



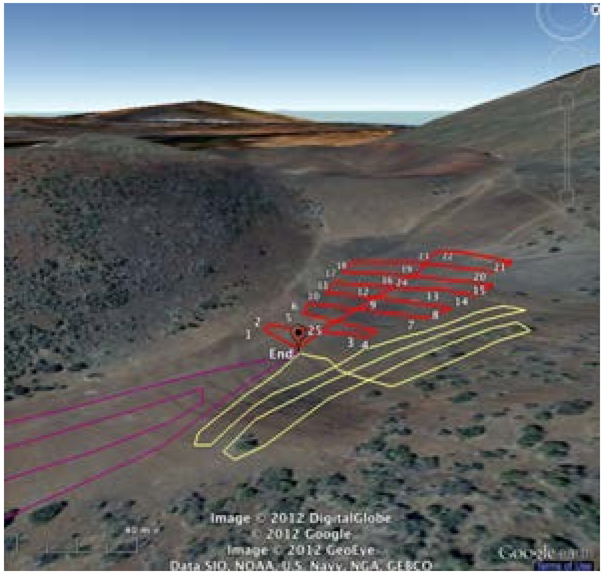
- 0.5-1000 m scale
- μ-dep.





Resolution matters

- E.g. gravity (on Earth) typical field procedure:
  - Regional survey: 0.5-2 km spacing, square grid
  - Local survey: 10-100 m apart along roads
  - Position (x,y,z) needs to be accurately known within inches (regional within 1 ft)
  - A good knowledge of rock densities in area is required to find anomalies
- E.g. magnetometer (on Earth) typical field procedure:
  - Airborne: line spacing ~200m, tie lines >10x line spacing
  - Fly draped (follow topography at constant height) is good for mining targets
  - Fly barometric (constant altitude) is good for oil (deeper targets)



RESOLVE field test Hawaii 2012

Definition of Reference Reserve Cases

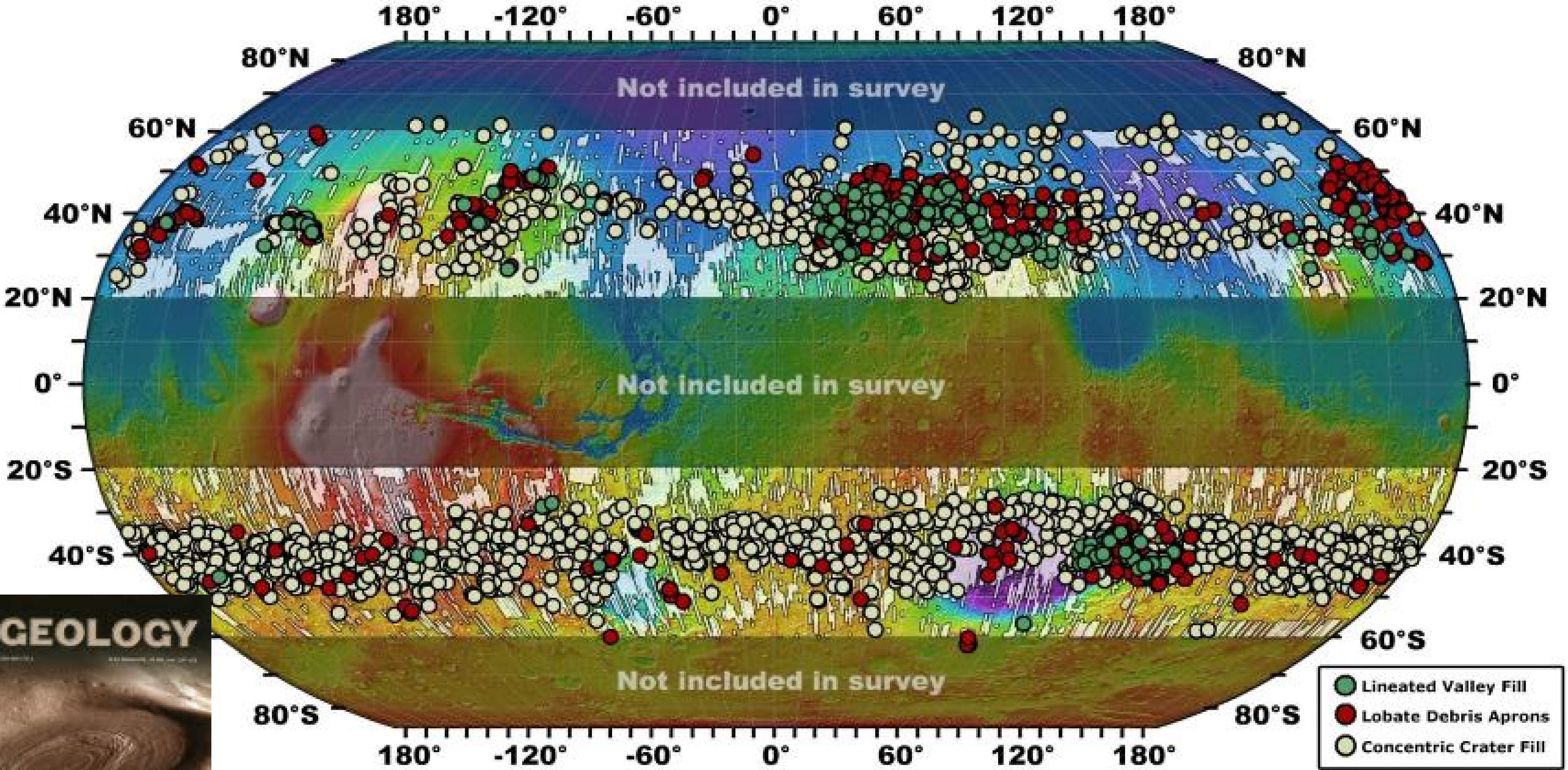
Four reference cases were chosen to represent the output of HLS[2]

Essential Attribute	A. Ice	B. Poly-hydrated Sulfate	C. Clay	D. Typical Regolith (Gale)
	Deposit Type			
Depth to top of deposit (stripping ratio)	variable (1-10m)	0 m	0 m	0 m
Deposit geometry, size	bulk	bulk	bulk	bulk
Mechanical character of overburden	sand	NA	NA	NA
Concentration and state of water-bearing phase within the minable volume				
–Phase 1	90% ice	40% gypsum[1]	40% smectite[2]	23.5% basaltic glass[3]
–Phase 2	--	3.0% allophane[4]	3.0% allophane[4]	3.0% allophane[4]
–Phase 3	--	3.0% akaganeite[5]	3.0% akaganeite[5]	3.0% akaganeite[5]
–Phase 4	--	3.0% smectite[2]	3.0% bassanite[6]	3.0% bassanite[6]
–Phase 5	--	--	--	3.0% smectite[2]
Geotechnical properties				
–large-scale properties ("minability"), e.g. competence, hardness	competent--hard	sand--easy	sand--easy	sand--easy
–fine-scale properties ("processability") , e.g. competence, mineralogy	no crushing needed	no crushing needed	no crushing needed	no crushing needed
The nature and scale of heterogeneity	variation in impurities	±30% in concentration	±30% in concentration	±30% in concentration
Distance to power source	1 km	1 km	1 km	100 m
Distance to processing plant	1 km	1 km	1 km	100 m
Amenability of the terrain for transportation	flat terrain	flat terrain	flat terrain	flat terrain
Presence/absence of deleterious impurities	dissolved salts	none	none	perchlorate?
First order power requirements	TBD	TBD	TBD	TBD
Not Considered				
Planetary Protection implications	TBD	TBD	TBD	TBD

1. ~20 wt% water, 100-150°C
2. ~4 wt% water, 300°C
3. ~1 wt% water, >500°C
4. ~20 wt% water, 90°C
5. ~12 wt% water, 250°C
6. ~6 wt% water, 150°C

Basis for Case A

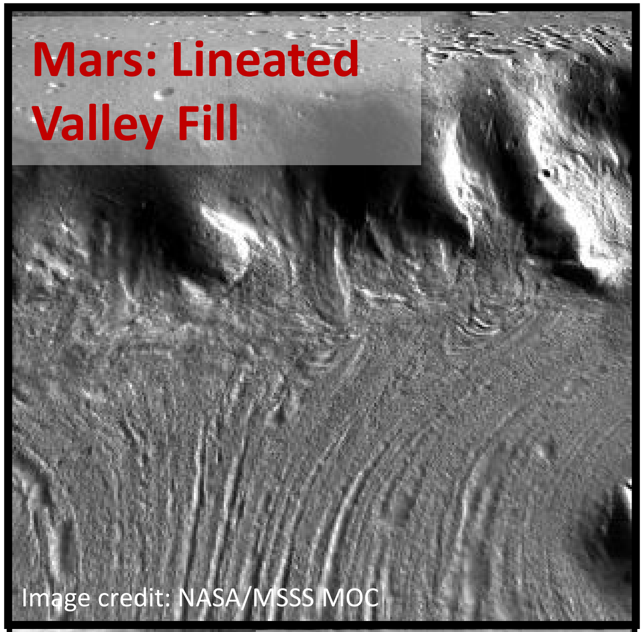
Map of Mars Glacial Features

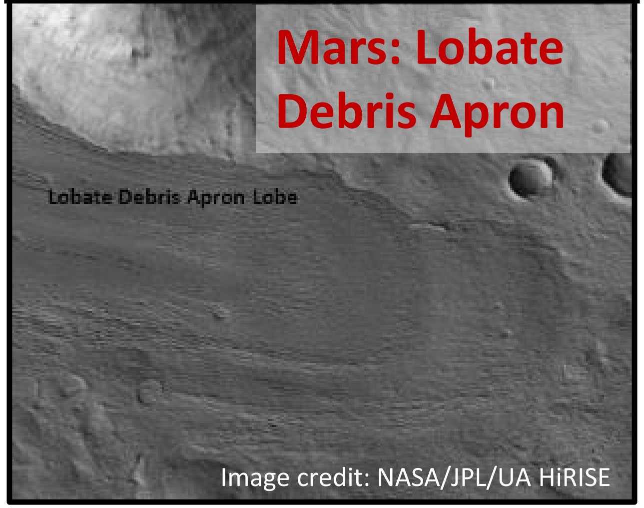


With many of these glacier-related geomorphic features, we have no information about whether residual ice remains, and if so, at what depth. Note that some lobate debris aprons have been confirmed to contain ice by radar investigations.

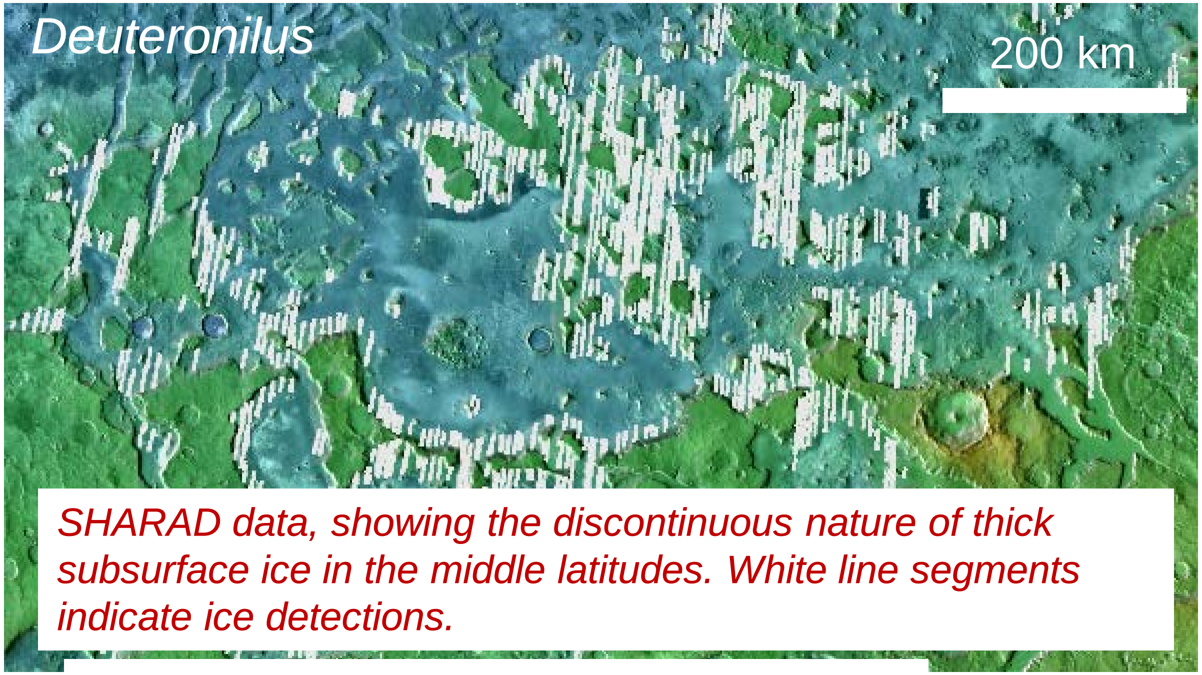
From Dickson et al., 2012; discussion with Jim Head acknowledged

Glacial Deposits on Mars: More Detail





- Mars glaciers are covered with a combination of sublimation till (the residue left as a result of ice sublimation) and rubble from nearby exposed outcrops.
- SHARAD data show a single, discrete surface echo over glaciers, implying that the thickness of the protective debris/dust cover is on order of the SHARAD vertical resolution (~10m) or less.
  - Could be between 1-10 m thick
- Glacial ice is 100s of meters thick.



SHARAD data, showing the discontinuous nature of thick subsurface ice in the middle latitudes. White line segments indicate ice detections.

Rummel et al. (2014) and Plaut (2016, Pers. Comm.)

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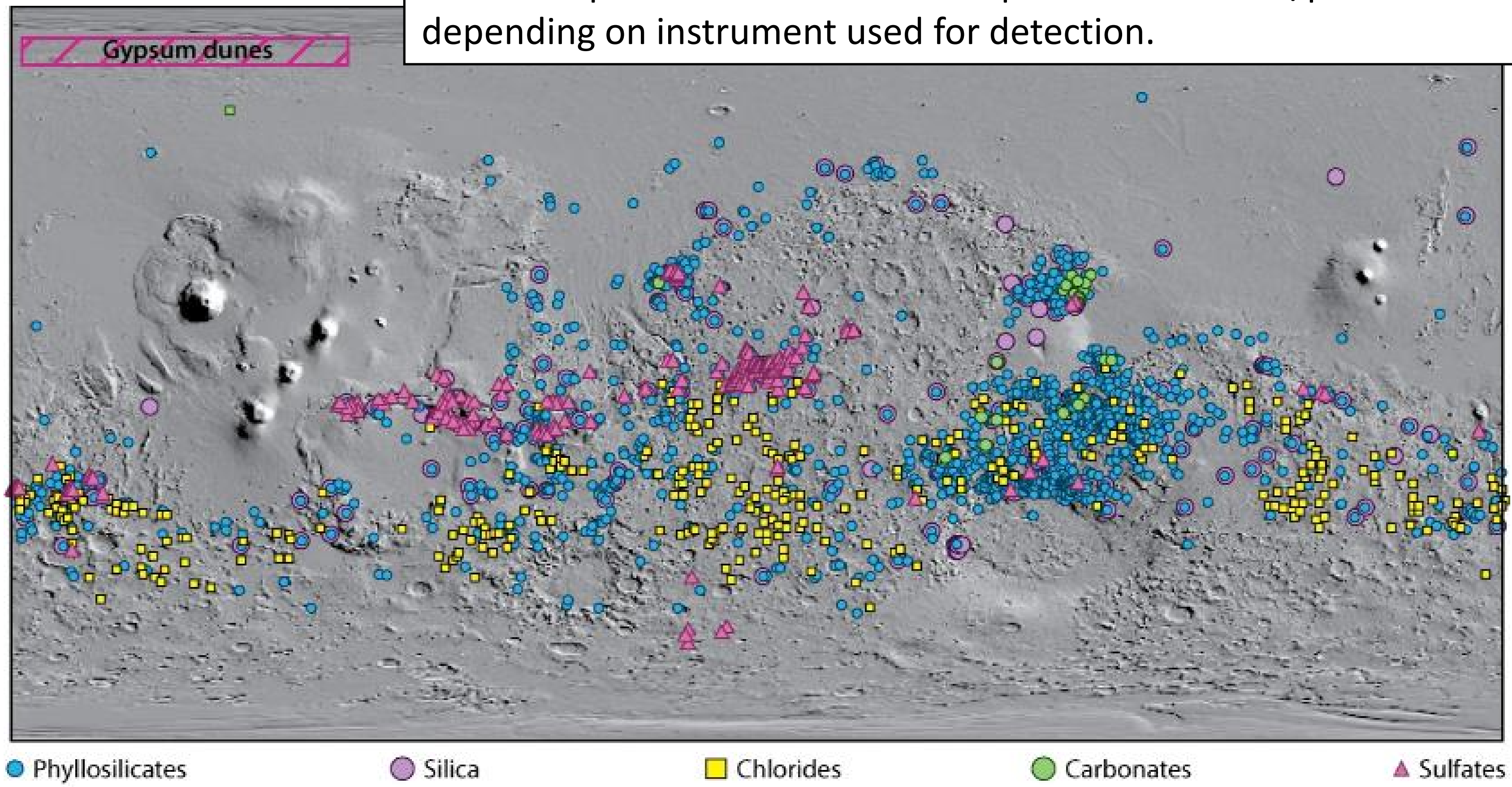
Basis for Cases B, C

Map of aqueous mineral detections

Note: footprint size is from 3x6km spots to 18-2000m/pixel depending on instrument used for detection.

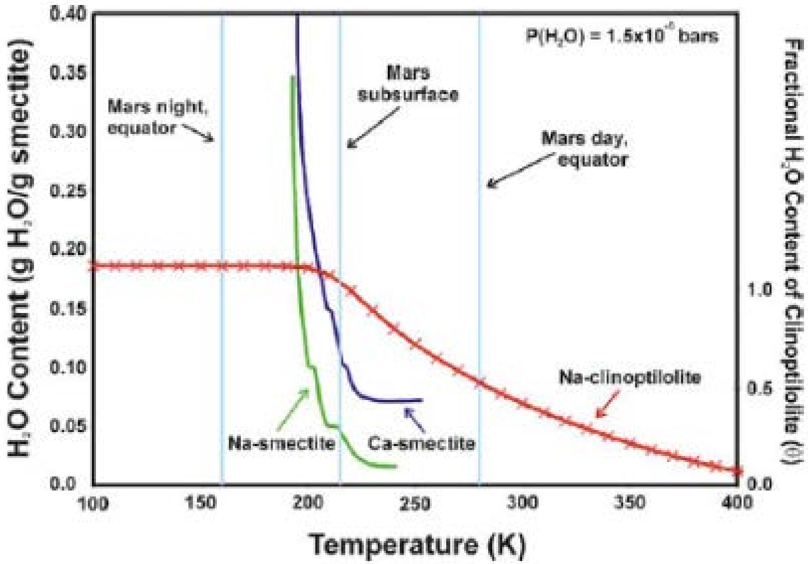


A master compilation of all mineral detections for Mars. Of relevance to this study are the phyllosilicate and sulfate detections.

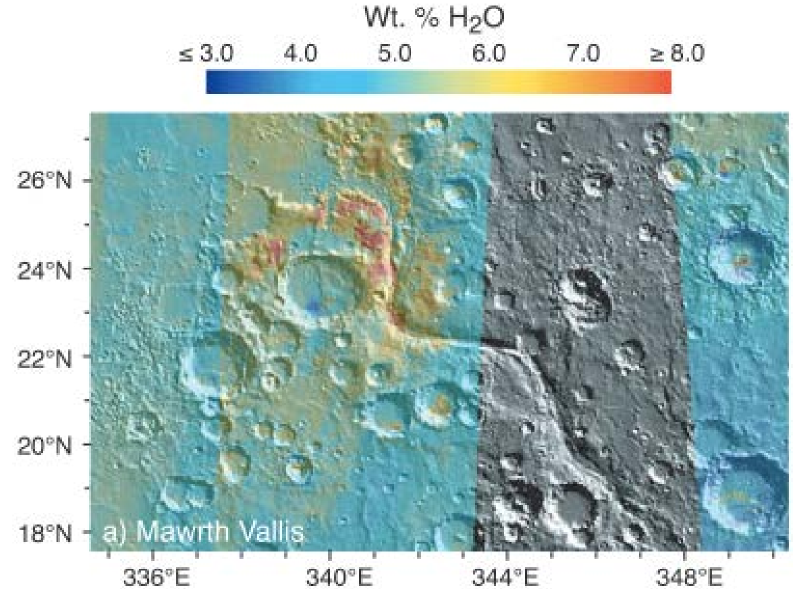
From Ehlmann and Edwards (2014)

Basis for Case C
Phyllosilicate Water Content

- For the purpose of this analysis, we assume a deposit consisting of smectite with an average of 4 wt% water content – note that this is lower than would be expected for terrestrial samples. It is also possible that phyllosilicate deposits with higher water contents could be identified.



Equilibrium hydration state of Na- and Ca-smectites (left axis) and of Na-clinoptilolite (right axis) as a function of T at a P (H_2O) of 1.5×10^{-6} bars. Note that at Mars surface conditions, Na-smectite has ~2 wt% water, and Ca-smectite has ~7 wt% water.

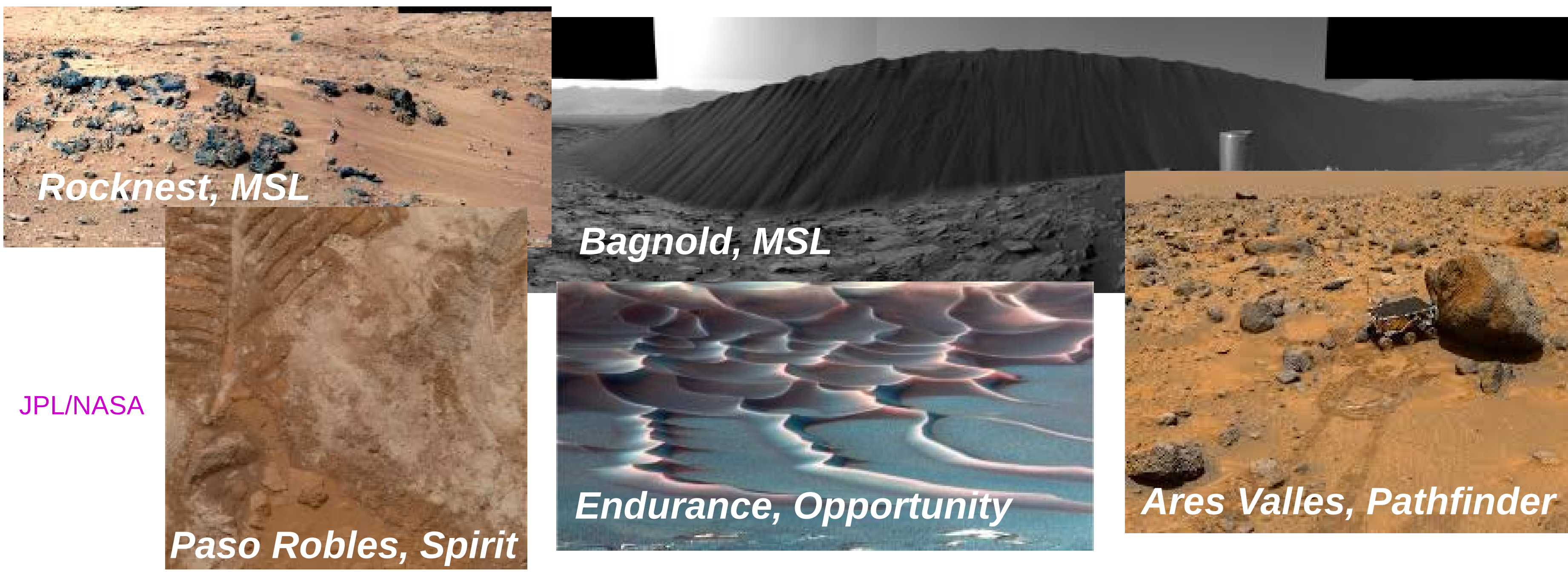


Modeled hydration maps for phyllosilicates in the Mawrth Vallis region. These regions exhibit water contents 2–3 times higher than surrounding terrains with similar albedo values, approaching values of 6–9 wt.% H_2O.

From Bish et al (2003) (left), Milliken et al (2007) (right), and discussion with Dave Bish and Ron Peterson

Basis for Case D (1 of 3)
Introduction to the Martian Regolith

- The broadest definition of "regolith", as it is used in a planetary sense, is: "The entire layer or mantle of fragmental and loose, incoherent, or unconsolidated rock material, of whatever origin (residual or transported) that nearly everywhere forms the surface, and that overlies more coherent bedrock." As such, this term as applied to Mars encompasses "soil", dunes, talus, ejecta, rubble, airfall dust, etc.



JPL/NASA

Although regolith, in the strictest sense, is present essentially everywhere on Mars, it is not all equally amenable to ISRU operations. Note significant differences in mechanical properties.

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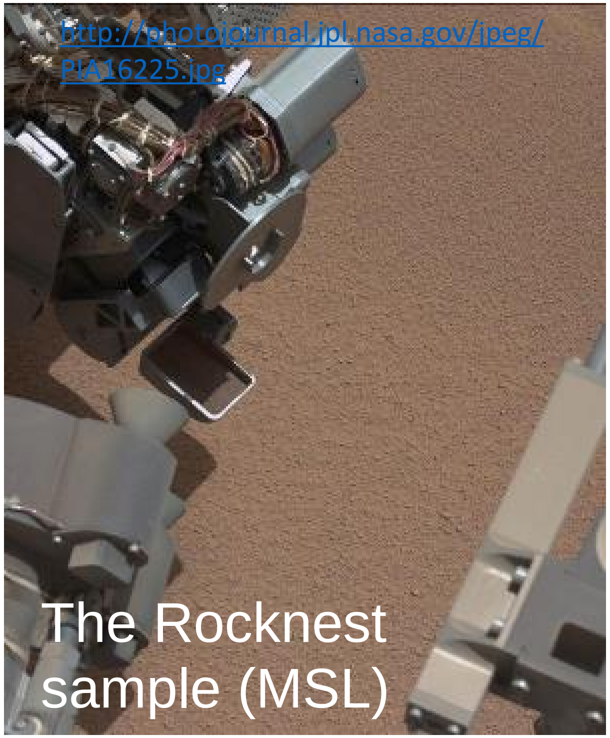
Basis for Case D (2 of 3)
What is the Regolith Made of? (Data from MSL)

- Mineralogy and total weight percent water used for reference Case D are based on data from MSL instruments: CheMin, SAM, and DAN.
- Case D mineralogy was based primarily on Rocknest, with additional minor components from John Klein and Cumberland to match the 1.5 wt% water indicated by the more conservative DAN results.

Mineral	Rocknest	John Klein	Cumberland
Plagioclase	29.8	22.4	22.2
Fe-forsterite	16.4	2.8	0.9
Augite	10.7	3.8	4.1
Pigeonite	10.1	5.6	8.0
Orthopyroxene		3.0	4.1
Magnetite	1.5	3.8	4.4
Anhydrite	1.1	2.6	0.8
Bassanite		1.0	0.7
Quartz	1.0	0.4*	0.1*
Sanidine	0.9*	1.2	1.6
Hematite	0.8*	0.6*	0.7
Ilmenite	0.7*		0.5*
Akaganeite		1.1	1.7
Halite		0.1*	0.1*
Pyrite		0.3*	
Pyrrhotite		1.0	1.0
Smectite		22	18
Amorphous	27	28	31

Crystalline and amorphous components (wt%) of the John Klein and Cumberland drill powders, compared with the Rocknest scooped eolian deposit. From plagioclase to pyrrhotite the estimated errors are ~6% of the amount shown for abundances of >20%, ~15% for abundances of 10 to 20%, ~25% for abundances of 2 to 10%, and ~50% for abundances of <2% but above detection limit. Phases marked with an asterisk are at or near detection limit. Relative 2σ errors are ~50% of the amount shown for smectite and ~60% for the amorphous component. [*Data primarily from CheMin, with smectite information from SAM.*]



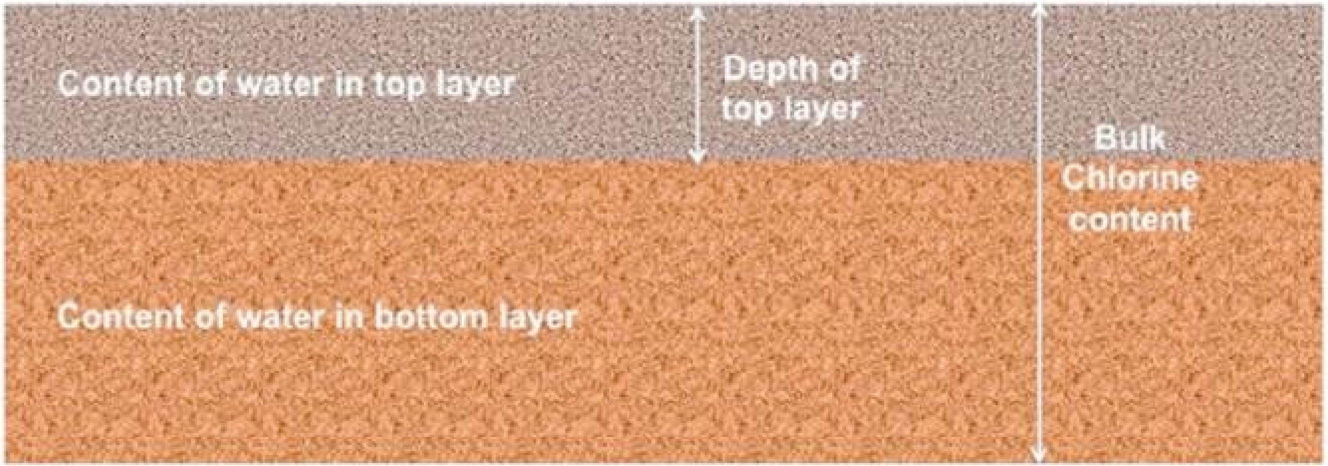
This material was analyzed in detail by MSL.

From Vaniman et al. (2014)

Basis for Case D (3 of 3)

DAN Measurements of Water Equivalent Hydrogen

- DAN measures total hydrogen over a footprint 3m wide and down to a depth of ~60 cm.
- Data from DAN are best modeled by a 2-layer structure
  - Upper layer has less H (average 1.5-1.7% WEH) than the lower layer (average 2.2-3.3% WEH).
  - Local anomalies as high as 6% WEH were measured in the first 361 martian sols; in later sols contents up to 10% WEH were measured.



Data from MSL's DAN instrument are best modelled using a two-layer subsurface structure. The top layer ranges between 10-30 cm thick. Water concentrations are in table below.

Note that the DAN instrument detects H, not water. The H could be present in hydrous minerals or as OH—it is almost certainly not present as liquid water. The "water-equivalent hydrogen" or WEH measured by DAN, is used to calculated the potential amount of "water" present using the models.

Table 3. Average Parameters of Soil for Four Different Ranges of the Curiosity Odometry

Odometry Ranges	0–455 m	455–638 m	638–876 m	876–1900 m
(1)	(2)	(3)	(4)	(5)
Top water (wt %)	1.68 ± 0.08	2.17 ± 0.12	1.50 ± 0.04	1.48 ± 0.03
Bottom water (wt %)	2.23 ± 0.08	1.41 ± 0.04	2.64 ± 0.06	3.33 ± 0.07
Vertical-average water (wt %)	2.07 ± 0.05	1.47 ± 0.03	2.31 ± 0.04	2.65 ± 0.04
Thickness of thetop layer (cm)	13 ± 1	6 ± 2	16 ± 1	22 ± 1
Content of absorption equivalent chlorine (wt %)	1.07 ± 0.02	1.14 ± 0.02	1.19 ± 0.01	1.17 ± 0.01

From Litvak et al. (2014) (top) and Mitrofanov et al. (2014) (bottom).

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Other Options Considered and Ruled Out: Extraction of Water from the Atmosphere

Some general facts and calculations:

1. At Mars surface pressure = ~6 mbar; atm density averages ~0.020 kg/m^3, water ~210 ppm = 0.0042 g(water)/m^3
2. 1 kg water is contained in 250,000 m^3 of atmosphere
3. To produce 5 mt water per yr, 0.57 kg would have to be produced per hour, which means 2400 m^3 (~1 Olympic sized swimming pool) of atmosphere would have to be handled per minute, assuming 100% recovery. This is equivalent to 84,000 CFM.
4. Martian atmosphere is at 1% of the pressure of the inlet pressure for compressors on Earth, thus an additional compression factor of 10^2 would have to be applied to get the same throughput.

→ We have not seen a credible method proposed for separating the water from an airstream of this scale, so we cannot estimate recovery efficiency.

→ The air-handling system implied by these calculations would be on the same order of magnitude as the largest air compressors known on Earth: ~600,000 CFM, requiring 65 megawatts to run, and roughly 5x5x10m in size.

AR140 MAN1 – the largest axial flow compressor for use in industrial applications (on Earth)

<u>CONCLUSION</u>: The mass, power, volume, and mechanical complexity of the system needed for this approach are far outside of what is practical for deployment to Mars.

Other Options Considered and Ruled Out: RSL, Permafrost, High Latitude Ice

Recurring Slope Lineae (RSL)

- Only occur on steep slopes – very difficult for mining/transport operations.
- By definition, RSL are transient (seasonal). If liquid water is present, it may be only temporary.
- Hydrated minerals likely present, but are not necessarily more concentrated than in our other cases.

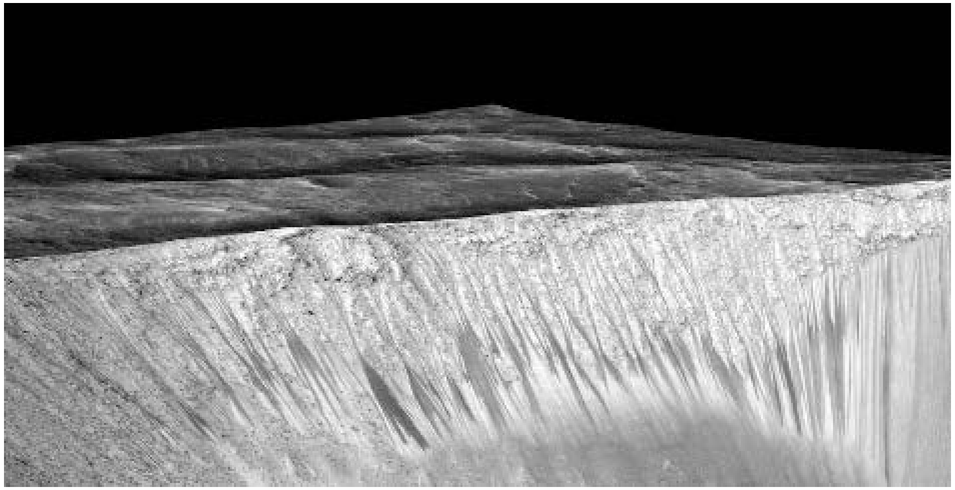


Image of a set of RSL (dark streaks) on a crater wall. Image credit JPL/NASA/Univ. Arizona

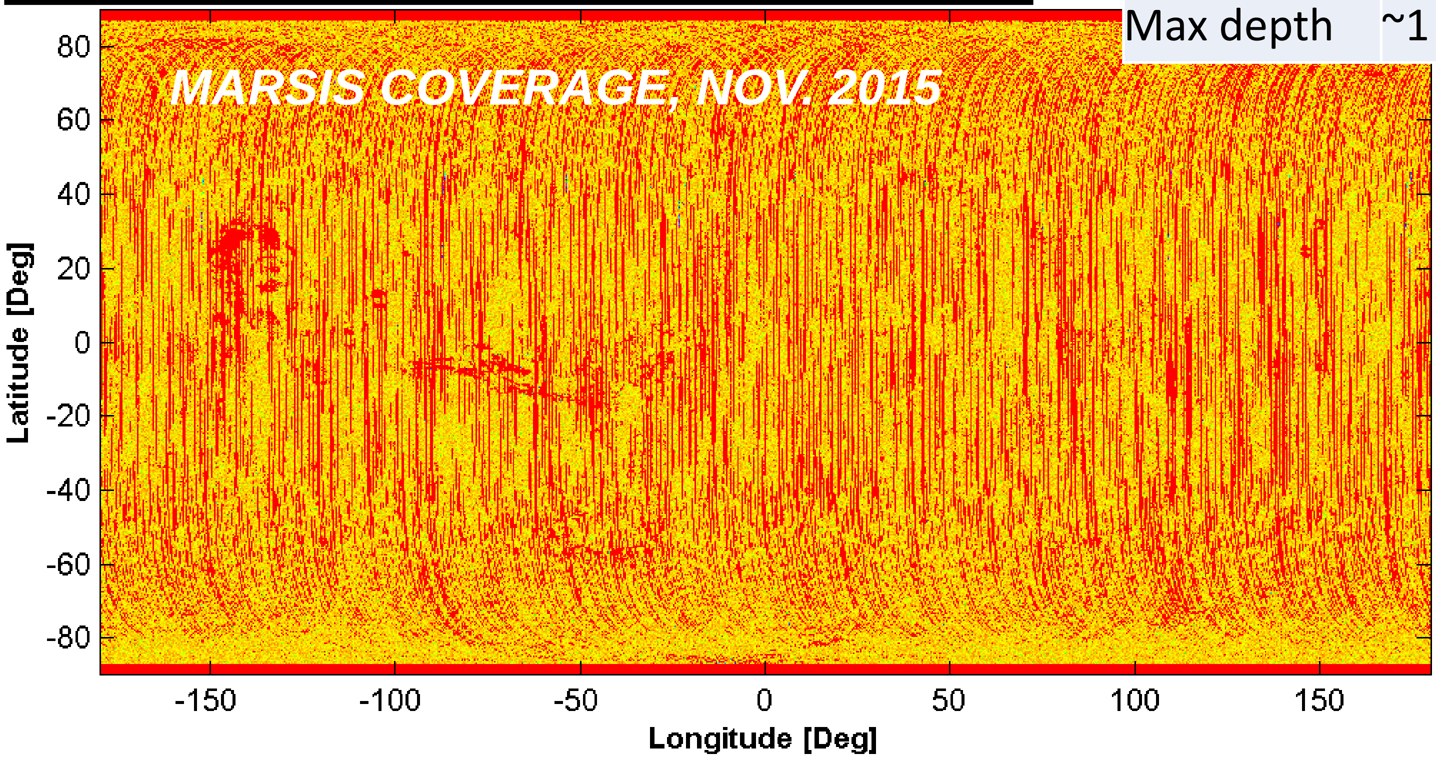
Permafrost: Although this exists (at high latitudes) on Mars, permafrost represents the existence of ice in the pore space of rock or soil, which is a low-grade variant of Case A (glacial ice). Since this will be less productive than glacial ice, we evaluate the latter here.

High Latitude Ice: Although large deposits of ice exist on Mars above 60° latitude, these exceed the latitudes set by our ground rules and assumptions.

Other Options Considered and Ruled Out: Deep Groundwater (1 of 2)

- MARSIS and SHARAD (radars) would be able to detect Mars groundwater (liquid water or brine in Mars bedrock) if it were present within the depths cited.
- ***<u>No such groundwater has been detected</u>*.**

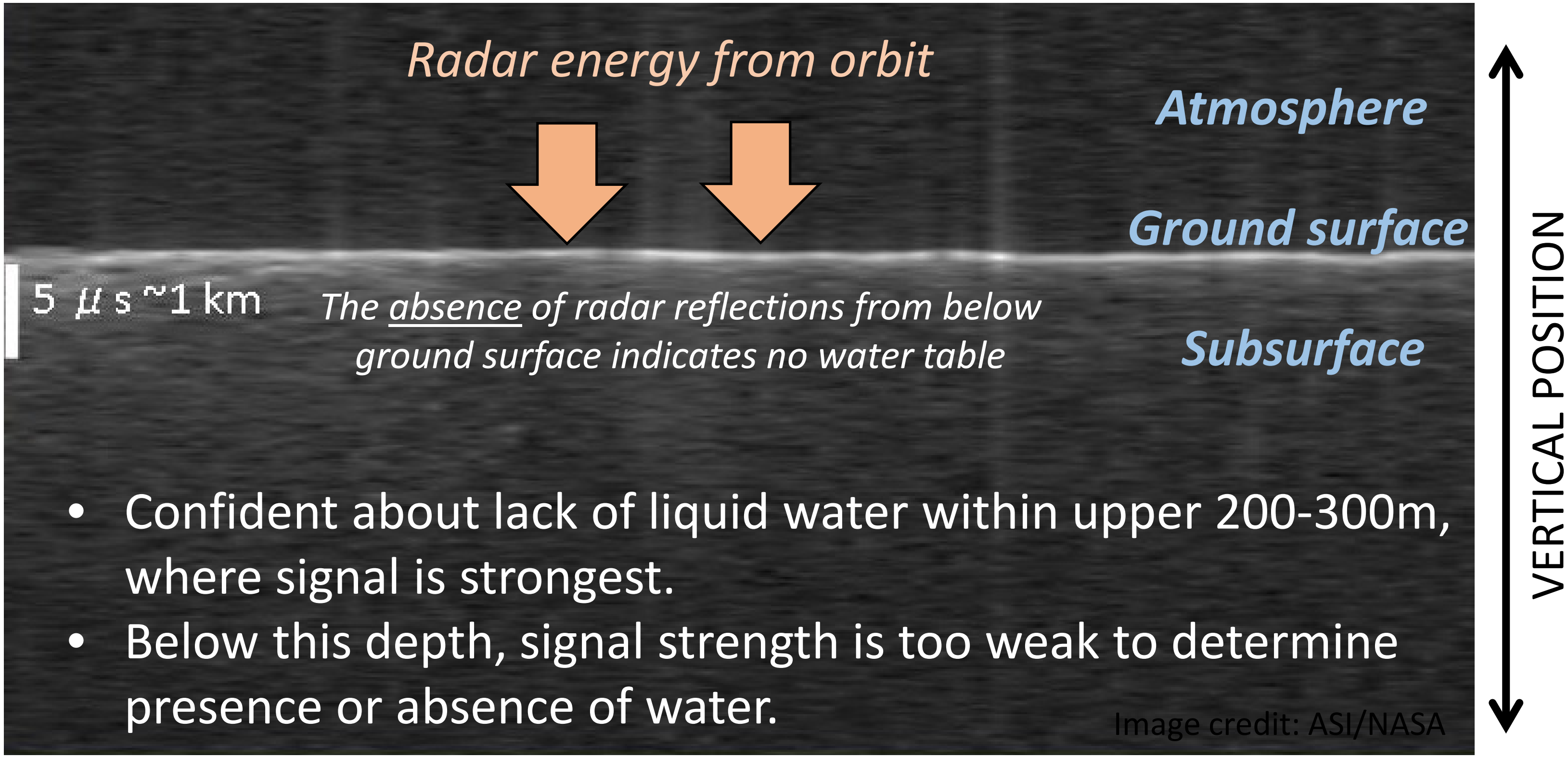
	MARSIS	SHARAD
Coverage	~69%	~31%
Spatial res.	~10 km	~0.5 km
Depth res.	~100 m	~10 m
Max depth	~1 km	~ 300 m



Map of Mars showing MARSIS data coverage as of Nov. 2015.
- *Yellow: Survey completed and no water detected (evidence of absence).*
- *Red: No data or SNR too low (absence of evidence)*

Contribution from Jeff Plaut; discussion with Rich Zurek, Serina Diniega

Other Options Considered and Ruled Out:
Deep Groundwater (2 of 2)



- Confident about lack of liquid water within upper 200-300m, where signal is strongest.
- Below this depth, signal strength is too weak to determine presence or absence of water.

MARSIS 5-MHz, radargram of the Athabasca region of Mars (4-7N, 149E). Images are taken along the track of the orbiter, using radar to detect subsurface features like water, which would show up as a reflective surface.

- Given the absence of detections, and the fact that the coverage map is rapidly filling in → *unlikely that there is groundwater at a depth shallower than ~200-300 m anywhere on the planet.*

Contributions from Jeff Plaut; Rummel et al. 2014

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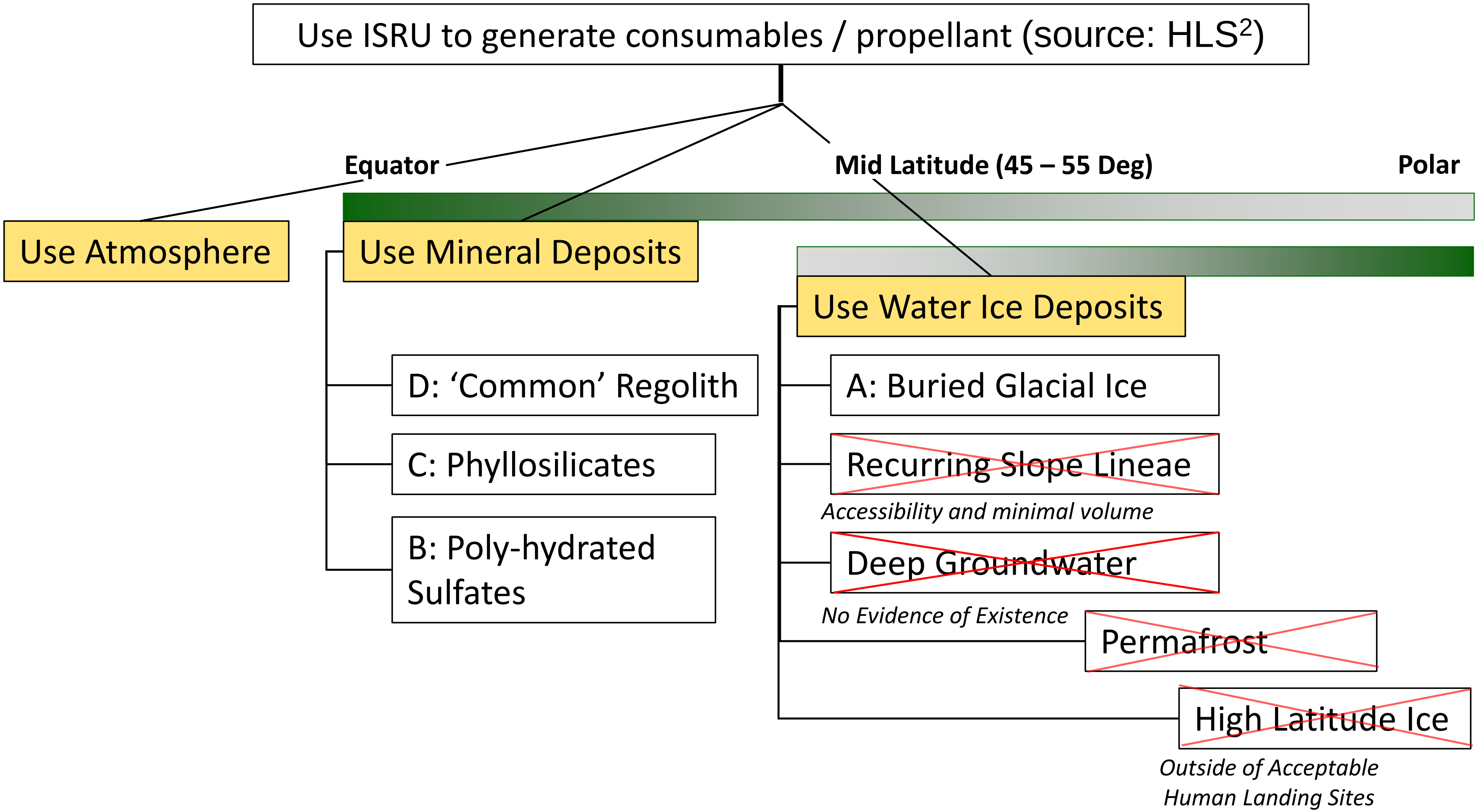
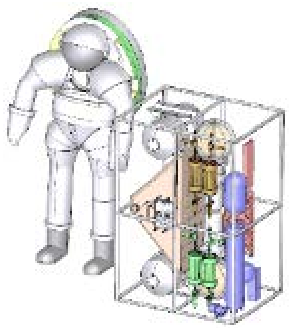
ISRU Resource Trade Tree



Abbud-Madrid, A., D.W. Beaty, D. Boucher, B. Bussey, R. Davis, L. Gertsch, L.E. Hays, J. Kleinhenz, M.A. Meyer, M. Moats, R.P. Mueller, A. Paz, N. Suzuki, T. van Susante, C. Whetsel, E.A. Zbinden, 2016, Report of the Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study; 90 p, posted April, 2016 at http://mepag.nasa.gov/reports/Mars_Water_ISRU_Study.pptx

Mars ISRU: Atmosphere & Water Resource Attributes

Atmosphere Processing



Atmosphere
- Pressure: 6 to 10 torr (~0.08 to 0.1 psi);
- >95% Carbon Dioxide
- Temperature: +35 C to -125 C
- **Everywhere on Mars;** Lower altitude the better
- Chemical processing similar to life support and regenerative power

Granular Regolith Processing for Water

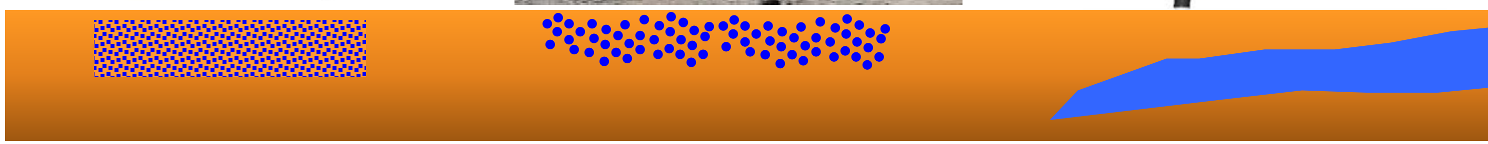
Mars Garden Variety Soil
- **Low water concentration 1-3%**
- **At surface**
- **Granular; Easy to excavate**
- 300 to 400 C heating for water removal
- Excavate and transfer to centralized soil processing plant
- **Most places on Mars**; 0 to +50 Deg. latitude

Gypsum/Sulfate Processing for Water

Gypsum or Sulfates
- Hydrated minerals 5-10%
- **At Surface**
- **Harder material:** rock excavation and crushing may be required
- **150 to 250 C heating for water removal**
- **Localized concentration in equatorial and mid latitudes**

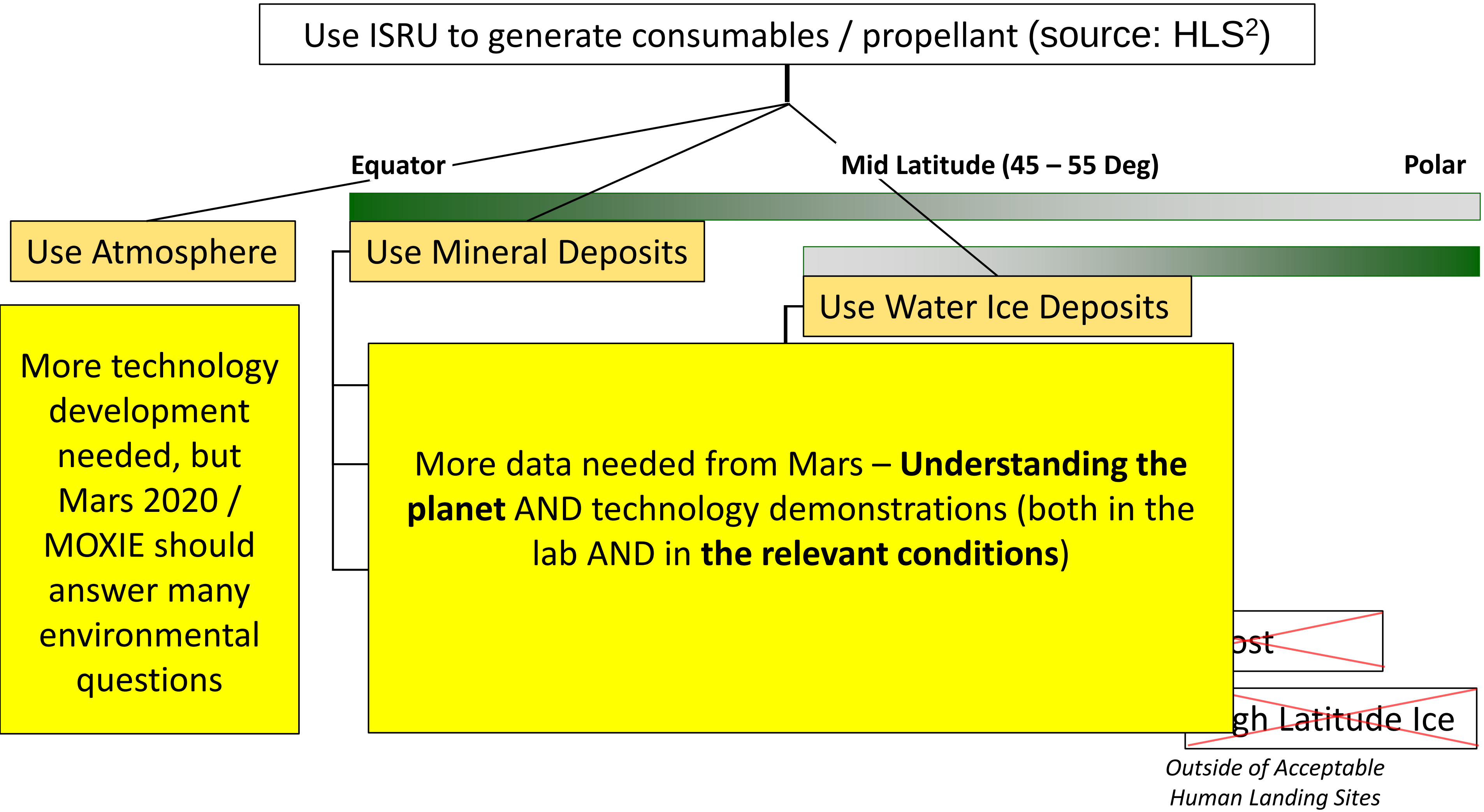
Icy Regolith Processing for Water

Subsurface Ice
- **90%+ concentration**
- **Subsurface glacier or crater:** 1 to 3 m from surface possible
- Hard material
- **100 to 150 C heating for water removal**
- Downhole or on-rover processing for water removal
- **Highly selective landing site for near surface ice or exposed crater;** >40 to +55 Deg. latitude



Increasing Complexity, Difficulty, and Site Specificity

ISRU Resource Trade Tree



Abbud-Madrid, A., D.W. Beaty, D. Boucher, B. Bussey, R. Davis, L. Gertsch, L.E. Hays, J. Kleinhenz, M.A. Meyer, M. Moats, R.P. Mueller, A. Paz, N. Suzuki, P. van Susante, C. Whetsel, E.A. Zbinden, 2016, Report of the Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study; 90 p, posted April, 2016 at http://mepag.nasa.gov/reports/Mars_Water_ISRU_Study.pptx

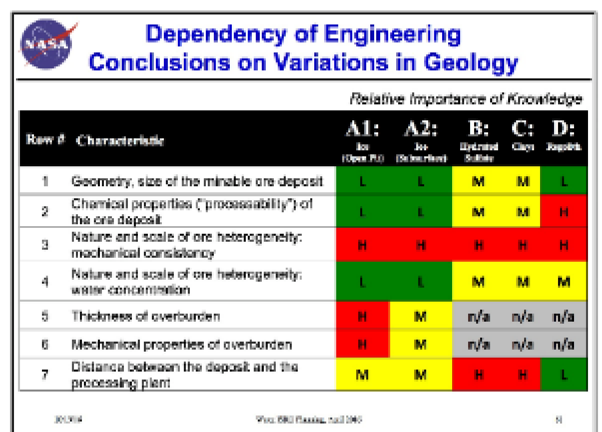
Key Properties of Resources (M-WIP)

- M-WIP Study from 2016 Identified key material properties impacting design and operations of Martian ISRU systems:
  - **For Water-bearing Granular Material:**
    - Geometry, Composition, Size of Deposits
    - Heterogeneity, particle size for MECHANICAL properties AND WATER CONTENT
    - ”Processability” of ore, including chemical properties
  - **For Subsurface Ice:**
    - Thickness of overburden
    - Mechanical Properties and composition/particle sizes of Overburden
    - ”Processability” of subsurface ice, including thickness, hardness, and contaminants
    - Stability of exposed ice (rate of sublimation)
  - **For Both:**
    - Distance / trafficability between resource deposit and ”point of use”

Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study

April 22, 2016

This "first-order" analysis of questions about supply-side planning related to potential water resource deposits on Mars was jointly requested by NASA-SMD and NASA-HEOMD in Jan. 2016.



Dependency of Engineering Conclusions on Variations in Geology

Relative Importance of Knowledge

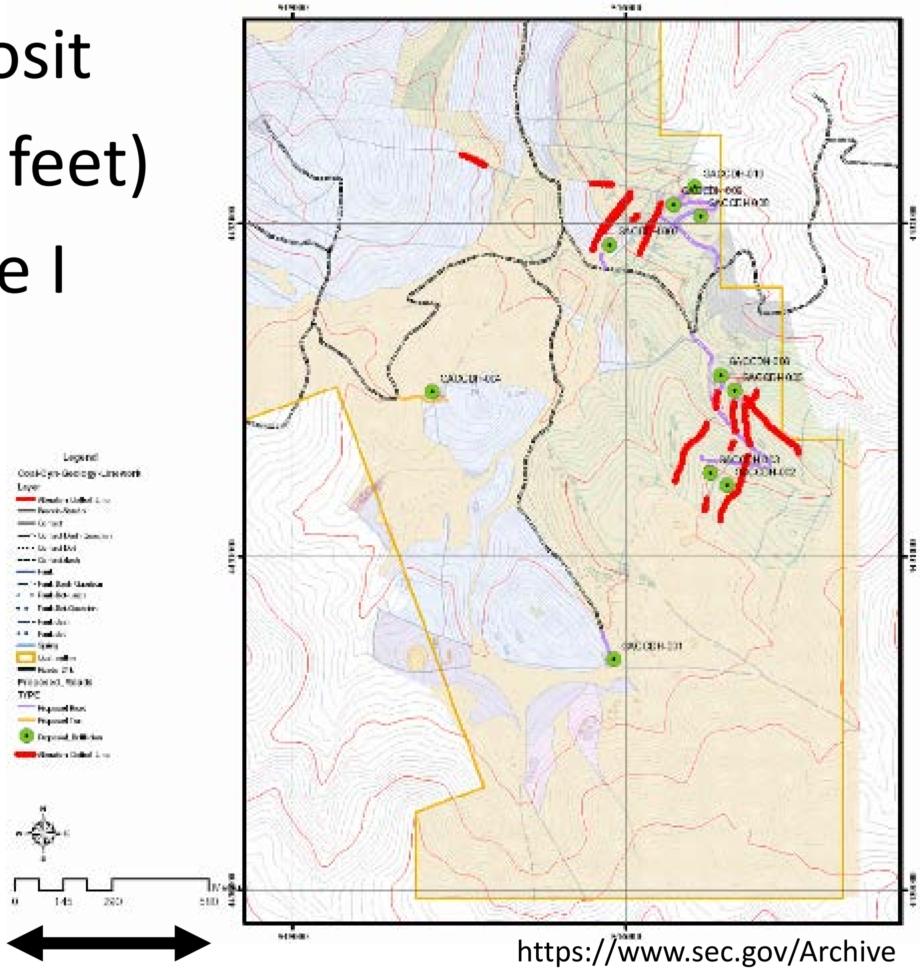
Row #	Characteristic	A1:	A2:	B:	C:	D:
1	Geometry, size of the minable ore deposit	L	L	M	M	L
2	Chemical properties ("processability") of the ore deposit	L	L	M	M	H
3	Nature and scale of ore heterogeneity: mechanical consistency	H	H	H	H	H
4	Nature and scale of ore heterogeneity: water concentration	L	L	M	M	M
5	Thickness of overburden	H	M	n/a	n/a	n/a
6	Mechanical properties of overburden	H	M	n/a	n/a	n/a
7	Distance between the deposit and the processing plant	M	M	H	H	L

Drilling & Surface Methods

- Presence (heterogeneity spatially)
- Minerology (Processing)
- Rock Quality Deteremination
- Soil Mechanical Properties (Excavation & Processing)
- Water Table

Drilling

- Example Potential Gold Deposit
- Phase I: 10 drill holes (3,000 feet)
- Phase II: 12,000 feet (if Phase I successful)
- Note Scale



500 m

https://www.sec.gov/Archives/edgar/data/1346022/000113707006000009/ex105coalcanyon.htm

Copper (sulfite) Example

Figure 7.7: Amygdaloidal Flow Top with Calcite and Epidote Filling Amygdules (Drill Core)

Figure 7.8: Fragmental Flow Top with Predominantly Calcite-Epidote Matrix (Drill Core

Figure 7.9: Scoriaceous Flow Top with Amygdular Clasts and Thick Interstitial Laminated Tuffaceous Sediment (Drill core)

Figure 7.10: Ophitic Basalt in Flow Interior (Drill Core)

Figure 7.14: Cross-section of Drill Holes on Grid Line 4+00E

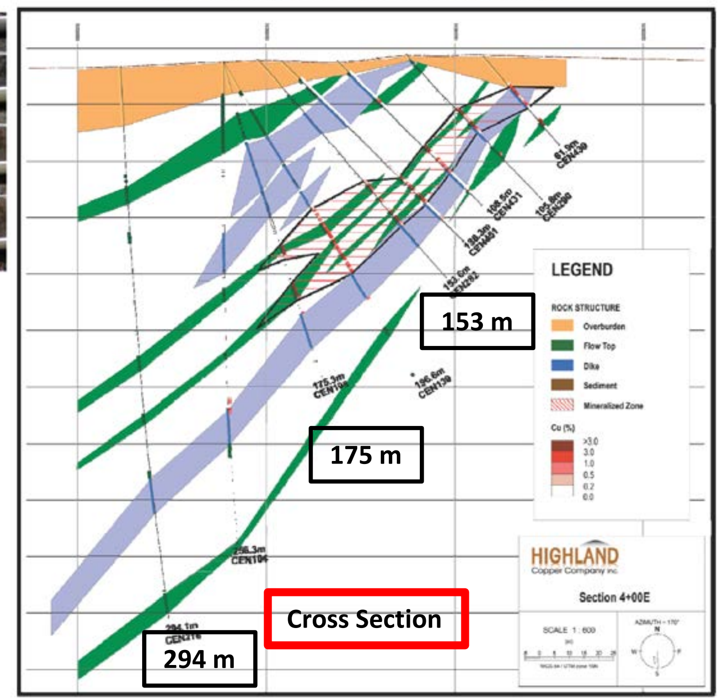
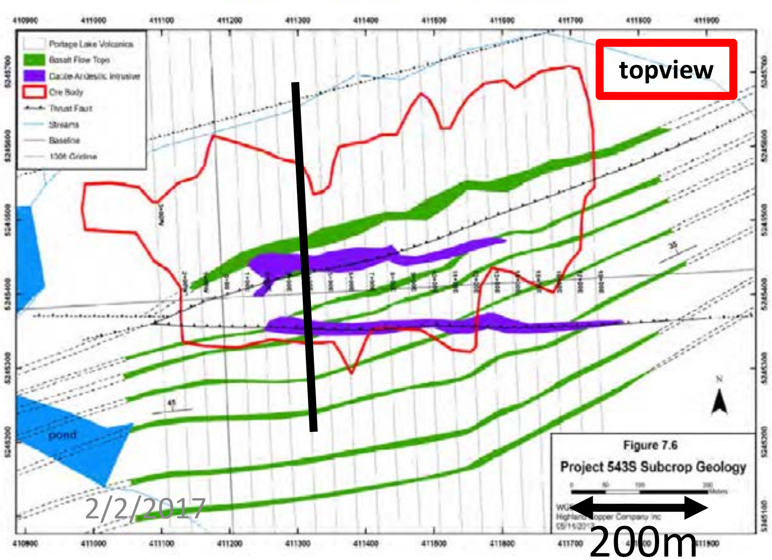


Figure 7.6: Project 543S Subcrop Geology



http://www.highlandcopper.com/i/pdf/reports/2014-10-09_43-101_543S%20Resource_FINAL.pdf

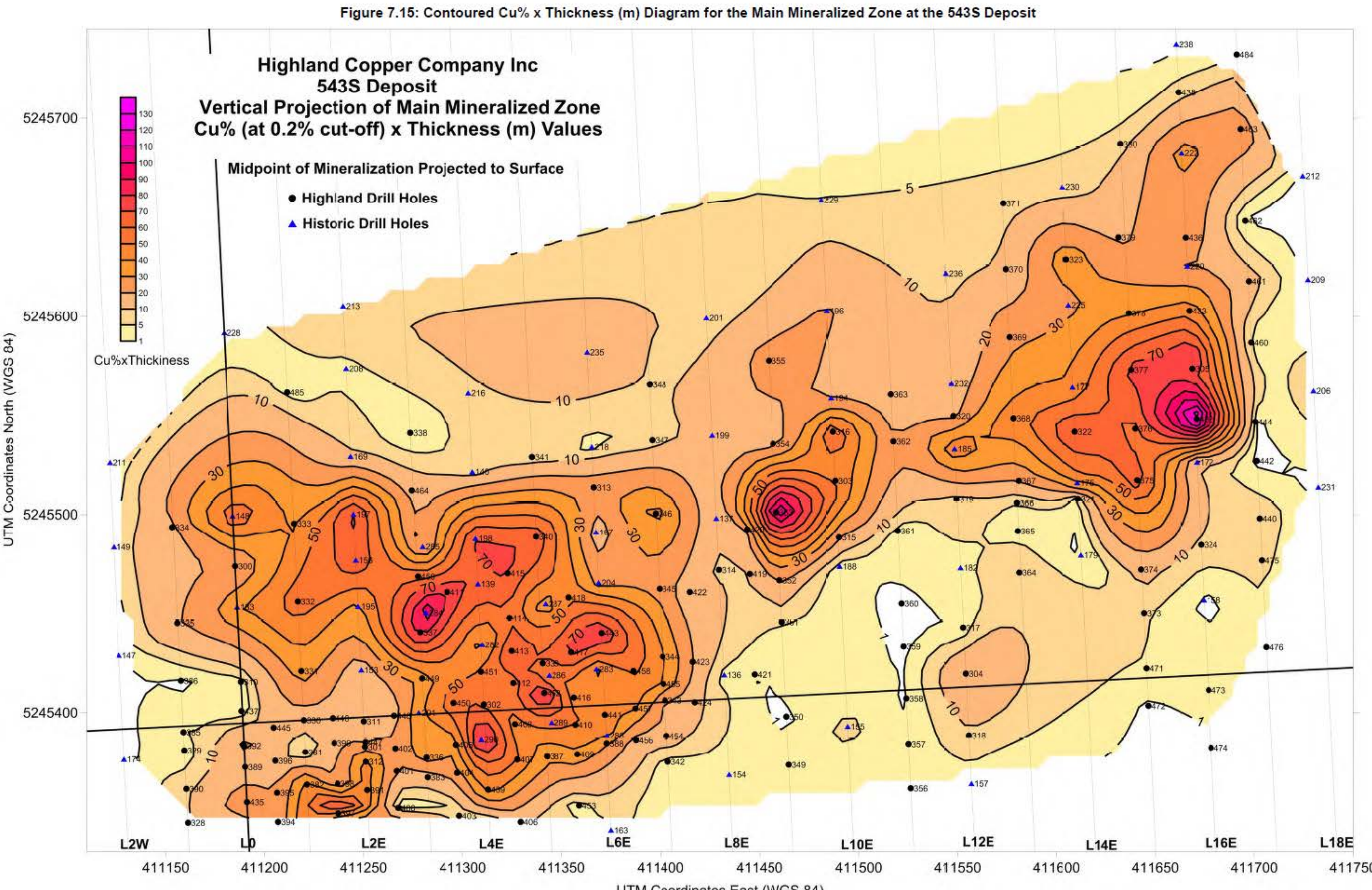
Total Drill Holes and Length

Table 12.1: Content of Diamond Drill Holes Available for the Resource Estimate for 543S

Hole Type	Hole Size	Number of Holes	Average Length (m)	Total Length (m)	Number of Assays
HKV (1970's)	BQ	81	199	16,722	1,654
GLM (1990)	NX	10	151	1,507	425
HCC (2012-2013)	NQ	129	162	20,963	16,794
HCC (2012-2013)	HQ	42	129	5,438	4,405

http://www.highlandcopper.com/i/pdf/reports/2014-10-09_43-101_543S%20Resource_FINAL.pdf

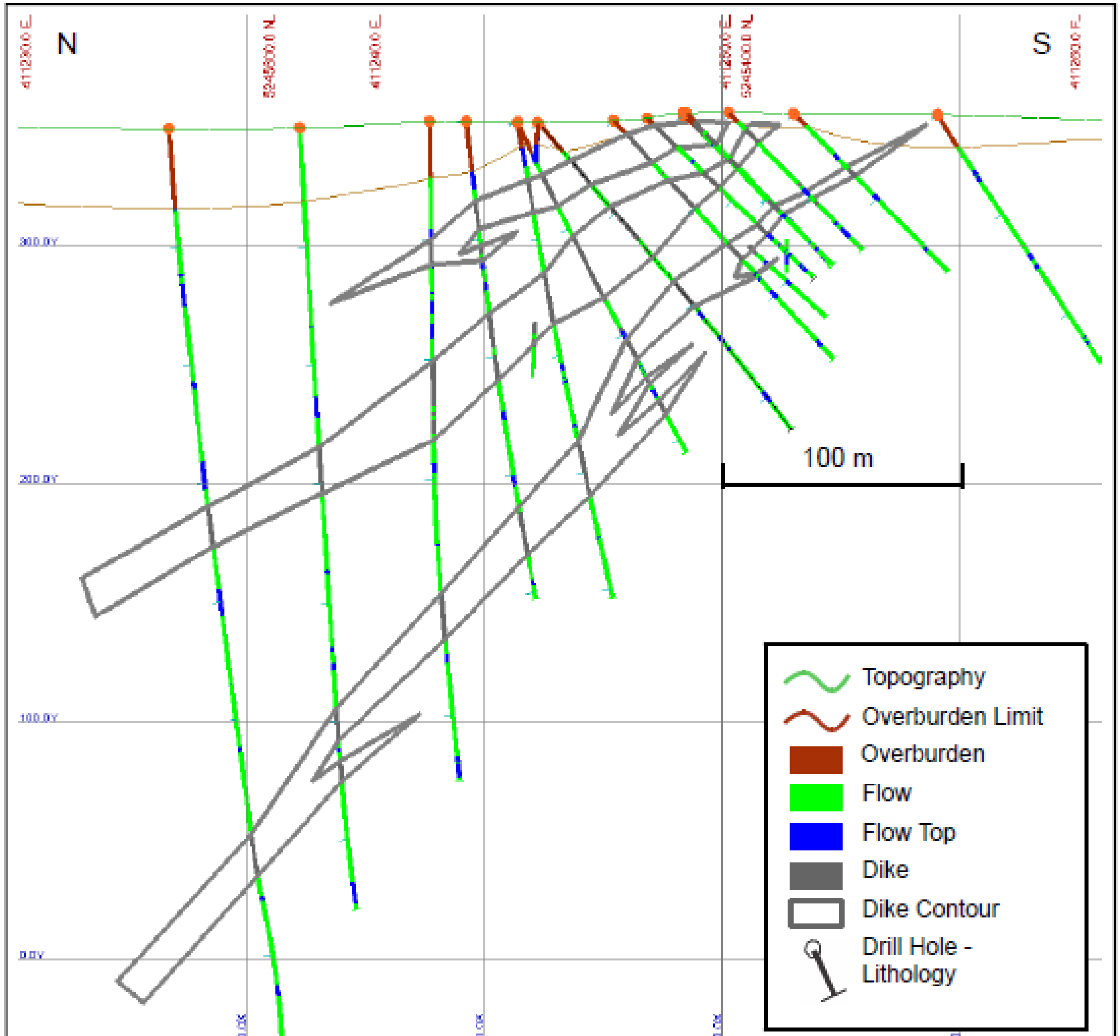
Interpretation of Drill Hole Data



http://www.highlandcopper.com/i/pdf/reports/2014-10-09_43-101_543S%20Resource_FINAL.pdf

Contour Interpretation

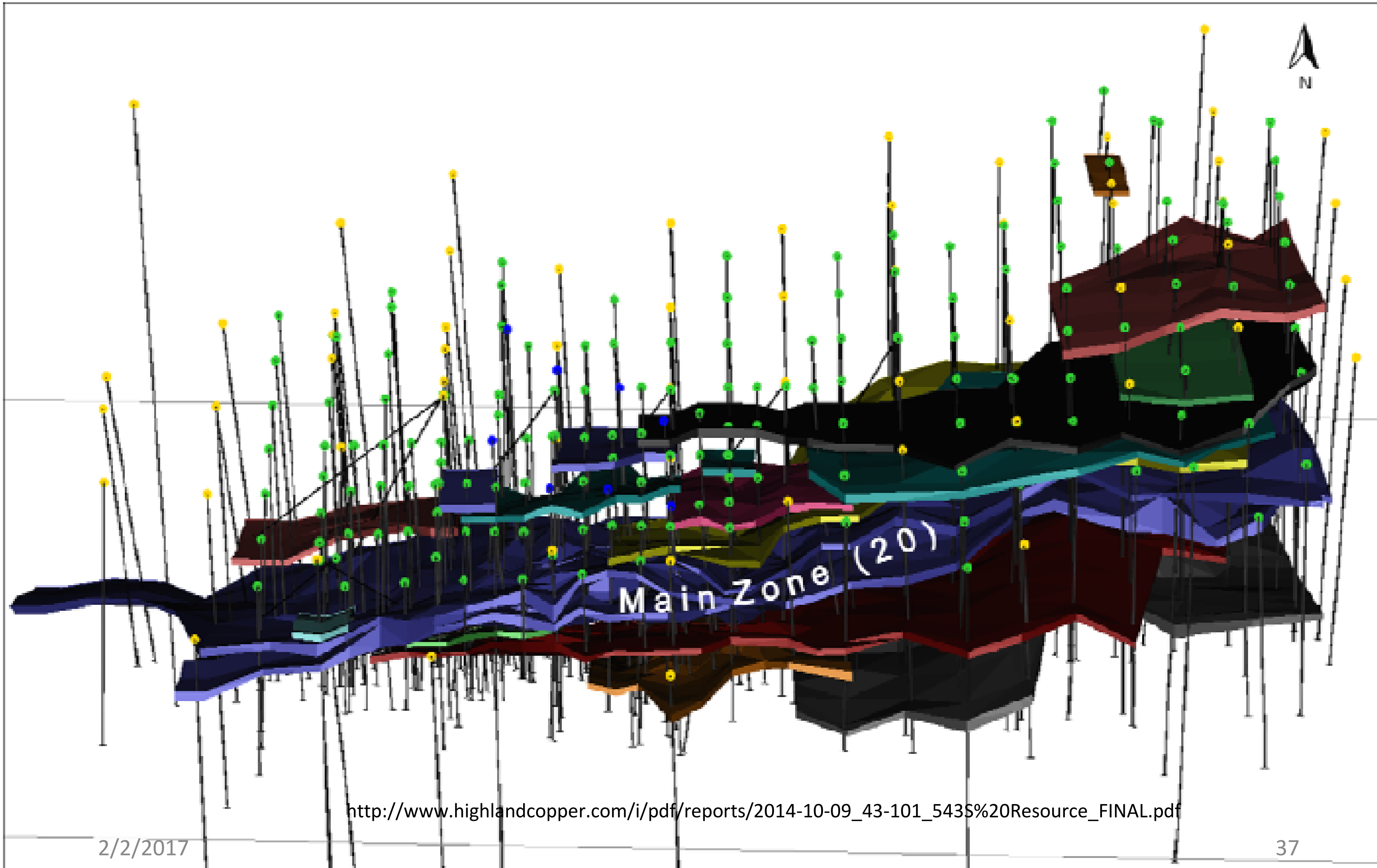
Figure 14.3: Section View of the Dike Contour Interpretation – Section 50200E Looking East



http://www.highlandcopper.com/i/pdf/reports/2014-10-09_43-101_543S%20Resource_FINAL.pdf

3D-Interpretation

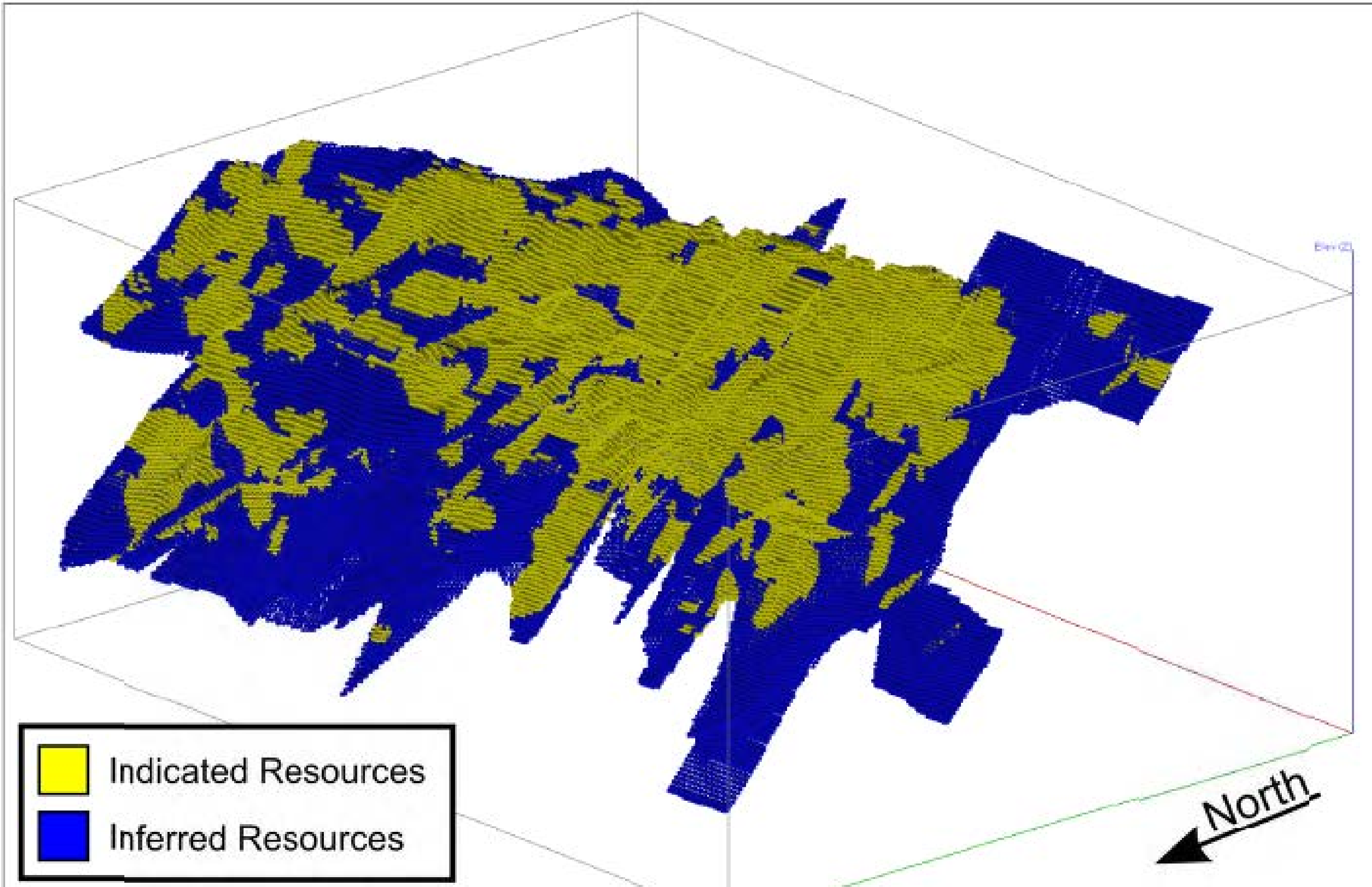
Figure 14.5: 3D View of the Drill Holes and the Domains (in various colors)



http://www.highlandcopper.com/i/pdf/reports/2014-10-09_43-101_543S%20Resource_FINAL.pdf

Indicated & Inferred Resource

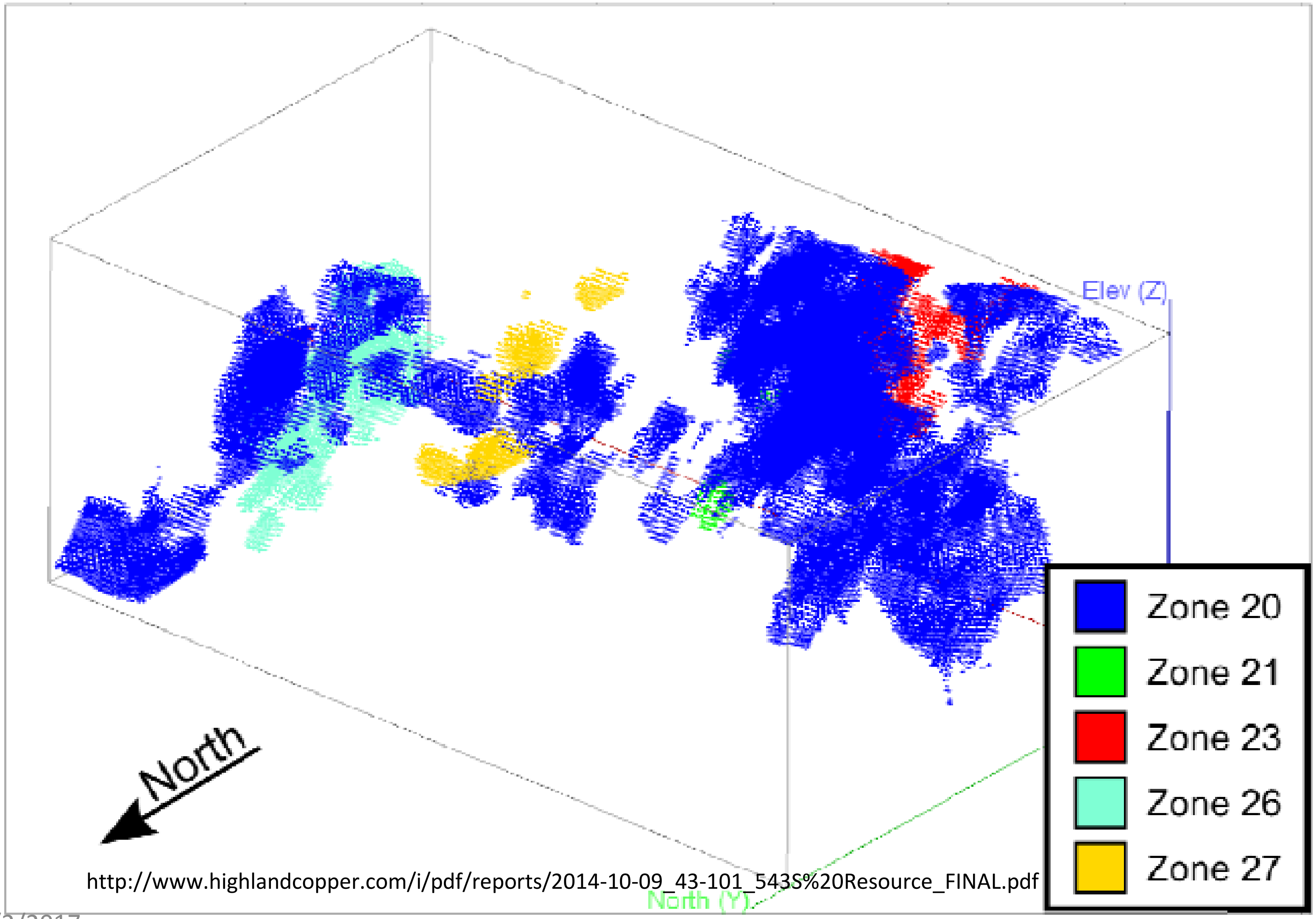
Figure 14.6: Resource Categories



http://www.highlandcopper.com/i/pdf/reports/2014-10-09_43-101_543S%20Resource_FINAL.pdf

Ore Body Analysis – Cut-Off Grade

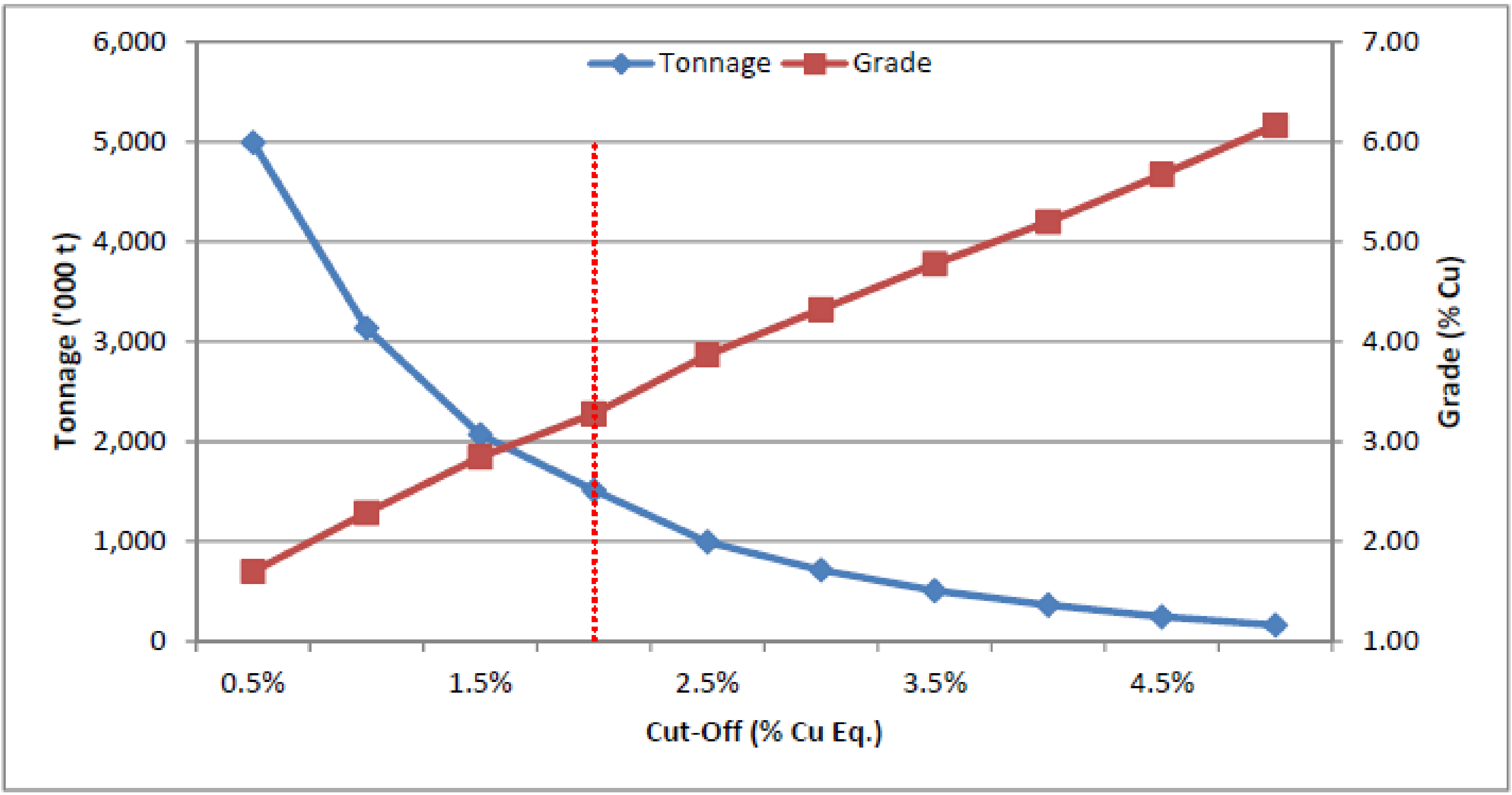
Figure 14.10: Constrained Mineral Resources Distribution by Zone – Cut-Off Grade of 1.9% Cu Eq.



http://www.highlandcopper.com/i/pdf/reports/2014-10-09_43-101_543S%20Resource_FINAL.pdf

Effect of Cut-Off Grade

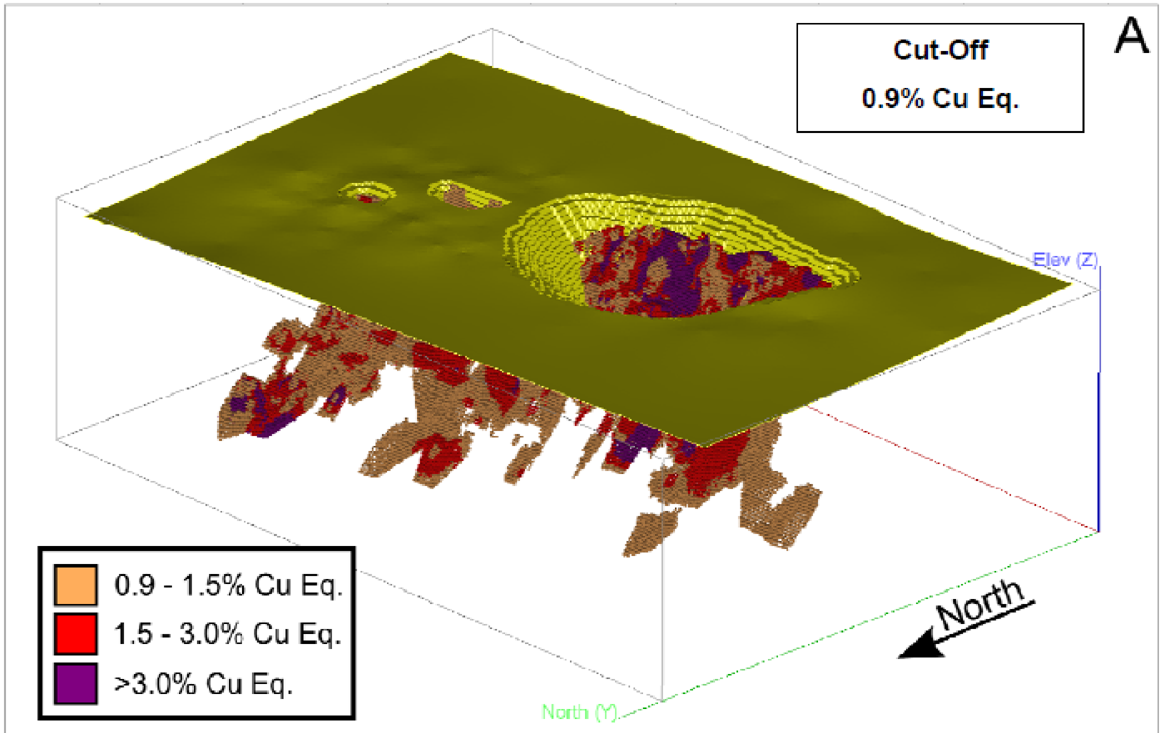
Figure 14.11: Grade-Tonnage Curves of Unconstrained Indicated Resource Estimate for Selected % Cu Eq. Cut-Offs (1.9% Cu Eq. Shown in Red Dashed Line)



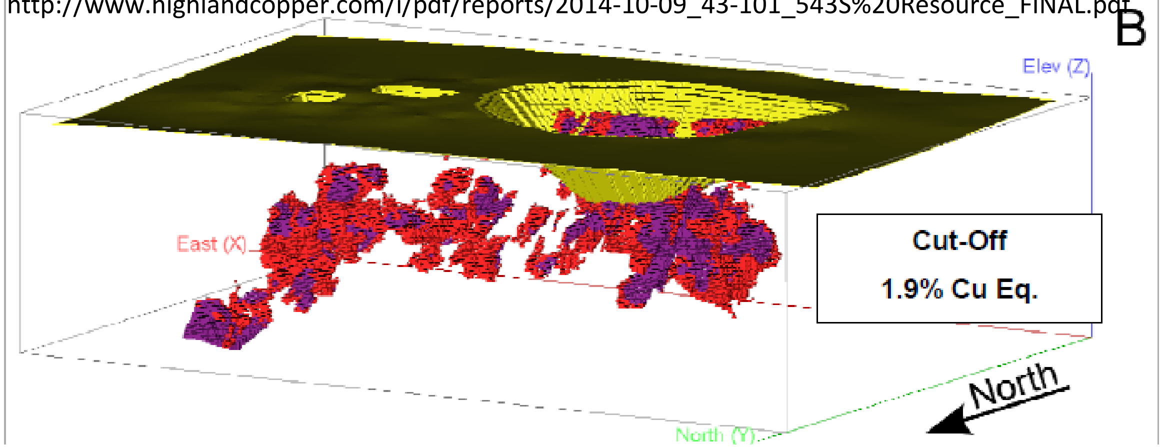
http://www.highlandcopper.com/i/pdf/reports/2014-10-09_43-101_543S%20Resource_FINAL.pdf

Open Pit and/or Underground

Figure 14.14: Hybrid Option Constrained Mineral Resource – (A) Open Pit Constrained Resource and (B) Underground Constrained Resources



http://www.highlandcopper.com/i/pdf/reports/2014-10-09_43-101_543S%20Resource_FINAL.pdf



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Conveying

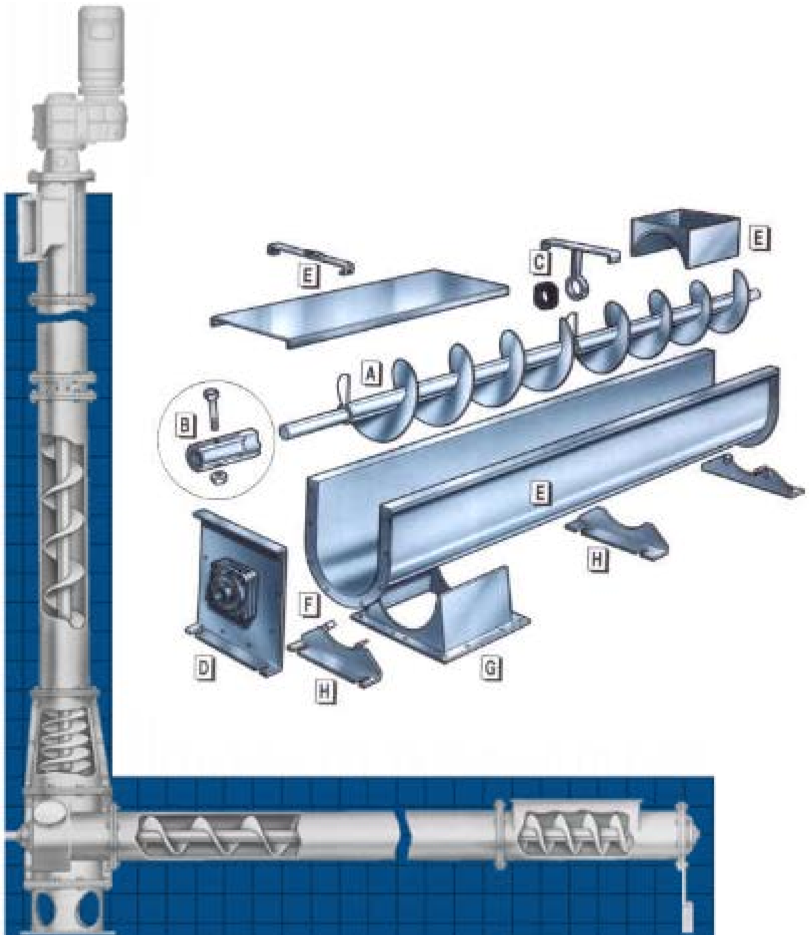
- Conveying technologies:
  - Augers (screw conveyors)
  - Pneumatic conveying,
  - Magnetic conveying pumping,
  - Vibratory conveying,
  - Belt coveyors
  - Bucket Elevators
  - Cable cars & Slurry Lines
  - Loaders/Haulers

Augers

- Drill vs. auger
  - Usually a combination: drill bit followed by auger flute
  - Function of drill is to break/loosen material and lead it to the auger
  - Function of the auger is to transport material

- Can transport
  - Liquids
  - Particles / fragments
  - Vertically, incline
  - Small and large scales

SCREW CONVEYOR



- **Advantages:**
  - Compact
  - Modular design: easy installation
  - Simple supports
  - High temperatures
  - Easily hermetically sealed
  - Extremely versatile:
    - “Dose”
    - Mixer
  - Distance up to 50 m
  - Several loading and unloading points possible

Michigan Technological University

SCREW CONVEYOR

- **Drawbacks:**
  - **Does not allow transport of large sizes of material**
  - **No fragile or delicate materials**
  - **Mostly for non abrasive materials**
  - **Bigger power requirements due to friction**
  - **Material pollution**
  - **Low material volume**

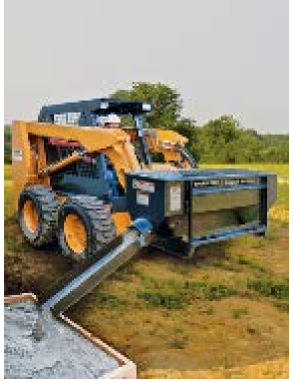
Augers used for ….

www.brockgrain.com

https://en.wikipedia.org/wiki/Archimedes'_screw

www.vanwalt.com

http://www.outdoorblog.net/outinmichigan/2012/09/05/ion-electric-ice-auger-2/



www.spartanequipment.com

http://falconindustries.com/industries/plastics

http://falconindustries.com/industries/mining

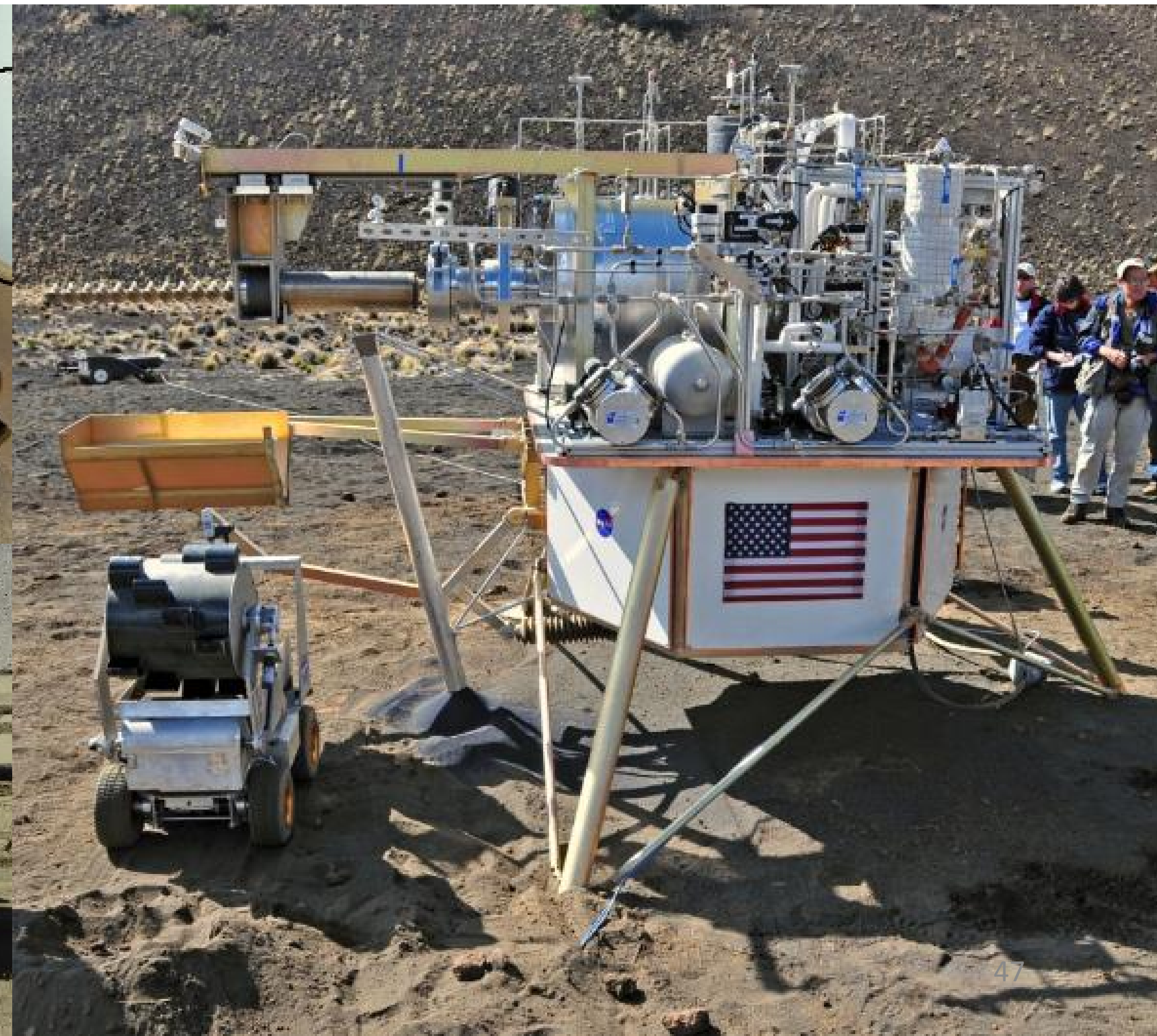
36 inch auger
www.boxeruk.com

www.directindustry.com

Augers for space applications

Bucketwheel & Auger testing at CSM

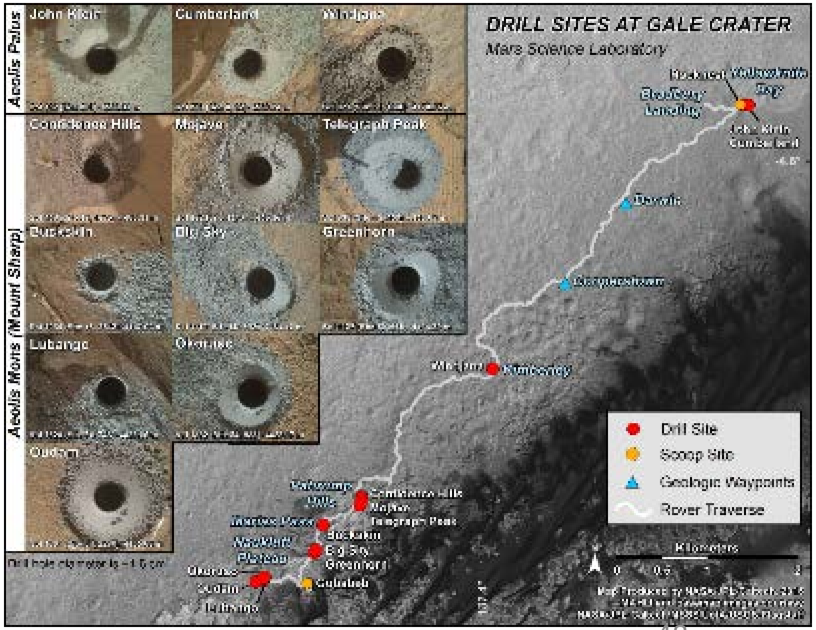
Mauna Kea field test setup: PILOT (Precursor In-situ Lunar Oxygen Testbed) (LMA /NASA)



Drilling in Space Applications

- Low power
- Low material volumes
- Modest depths (10's of meters)

Honeybee Robotics Asteroid Hopper concept (Honeybee Robotics)

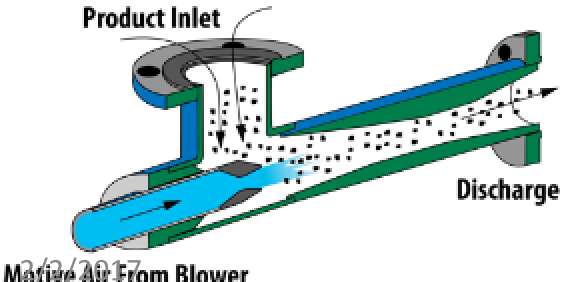


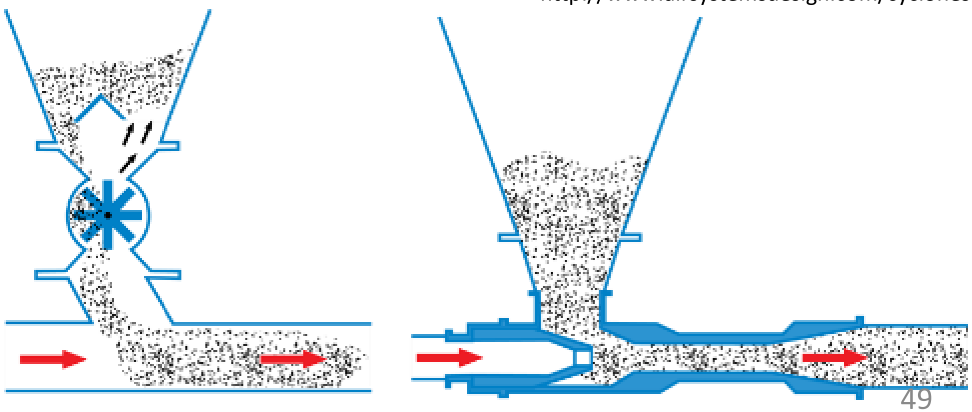
Curiosity Drill Sites at Gale Crater (NASA JPL)

Pneumatic Conveyance

- Foundries - Eliminating screw conveyors and dense phase systems handling foundry dust and sand
- Power - Conveying sorbents (limestone, CaCO3, MgO), coal, ash
- Building Materials - Fiberglass, gypsum, sand, roofing tiles
- Ceramics/Tiles - Conveying sand, grout components, aggregate
- Cement - Reclaim from dust collectors, aggregate, additives.
- Plastic Compounding - Conveying pellets filled with as much as 50% fiberglass
- Mining - Handling hot product from calciners, dust
- Glass - Handling silica, glass frit

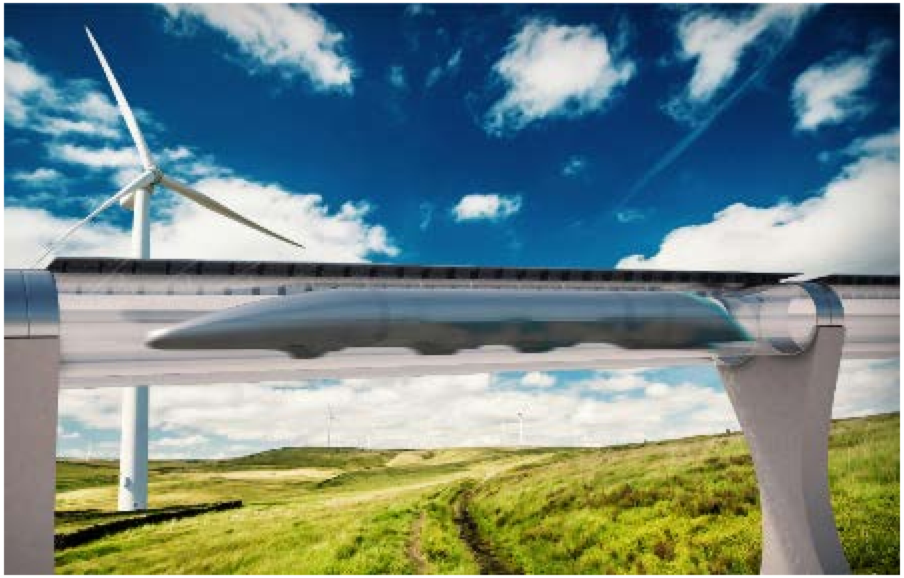
http://www.airsystemsdesign.com/cyclones.html





http://www.foxvalve.com/lt_solid_ce.aspx

Pneumatic Conveyance



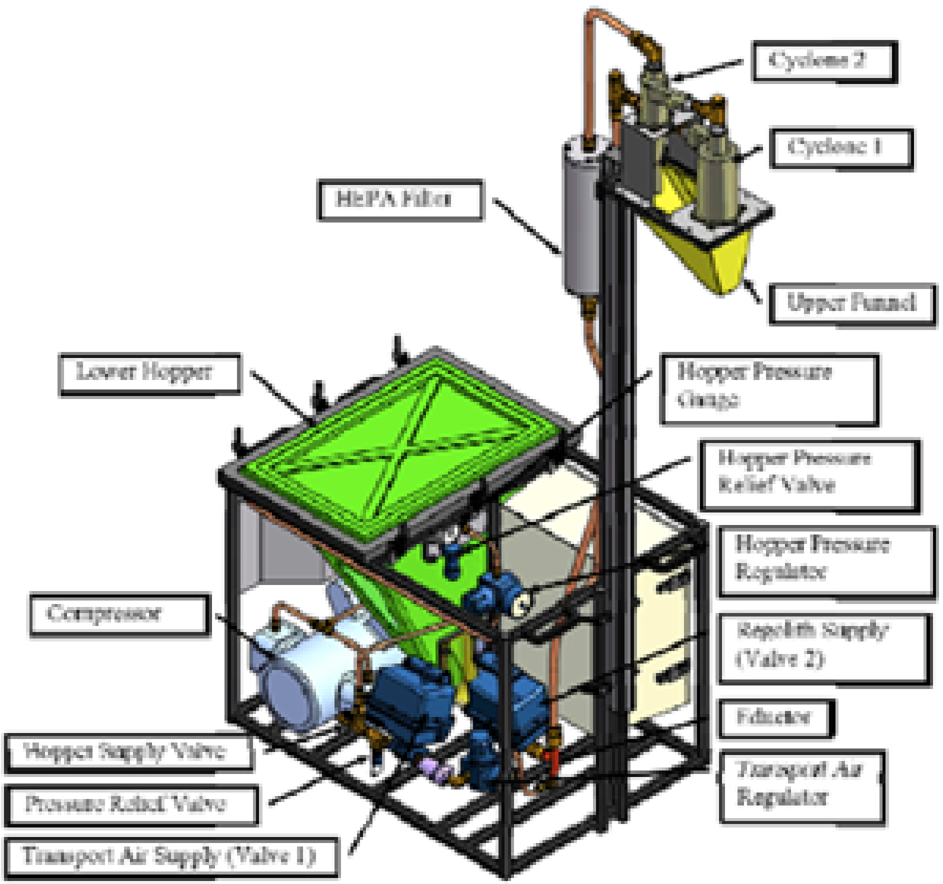
http://news.nationalgeographic.com/energy/2015/06/150602-Musk-sonic-hyperloop-gets-California-stretch/#/3_hyperloop_hyperloop_concept_nature_02_transparent_copyright_2014_omegabyte3d_c.jpg

http://www.nydailynews.com/life-style/eats/restaurant-installs-pneumatic-tubes-deliver-dishes-article-1.1562480

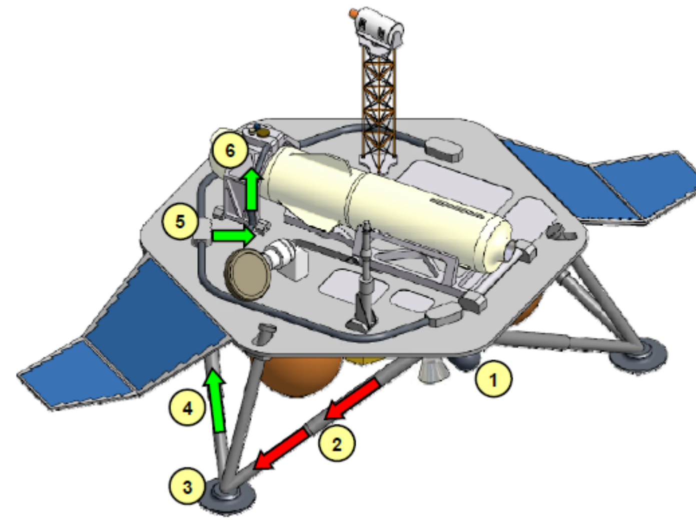
http://www.sbs-ky.com/portfolio-item/pneumatic-tube-systems/

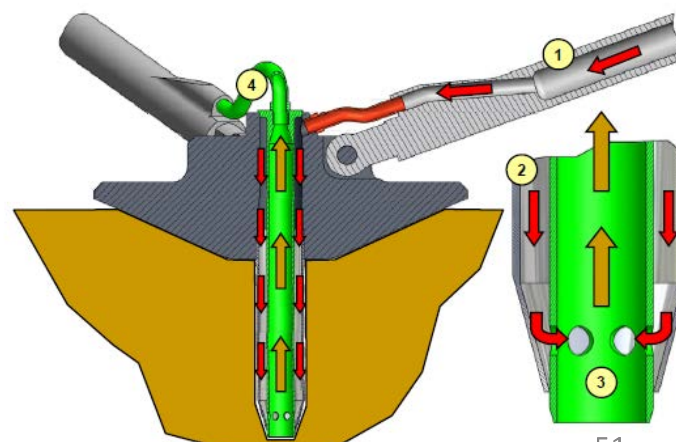
Pneumatic Conveyance in Space Applications

- Material Transport
- Requires very little gas



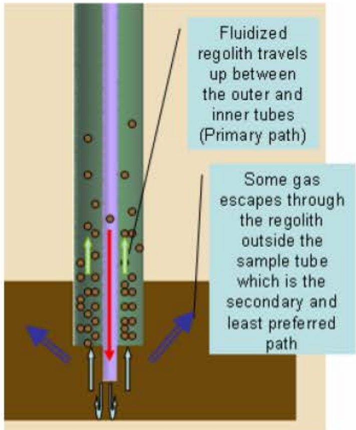
Honeybee Robotics



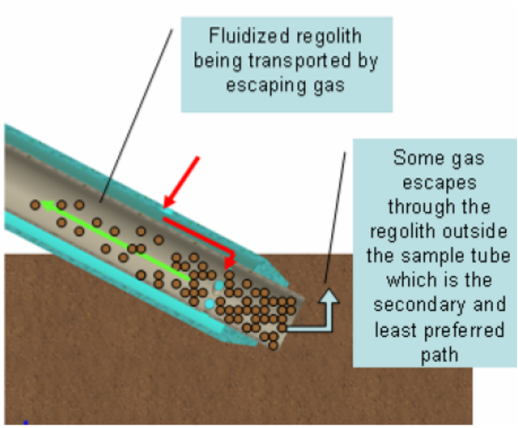


IEEEAC paper#1082, Version 5, Updated 2009:11:01

Pneumatic Conveyance for Space Applications

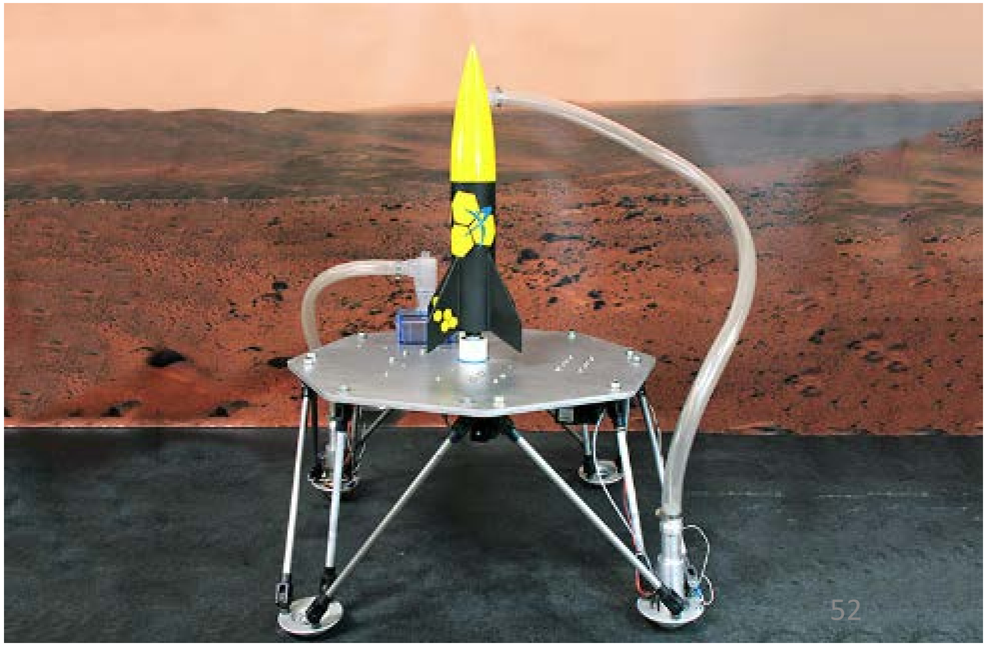


Plunge Method



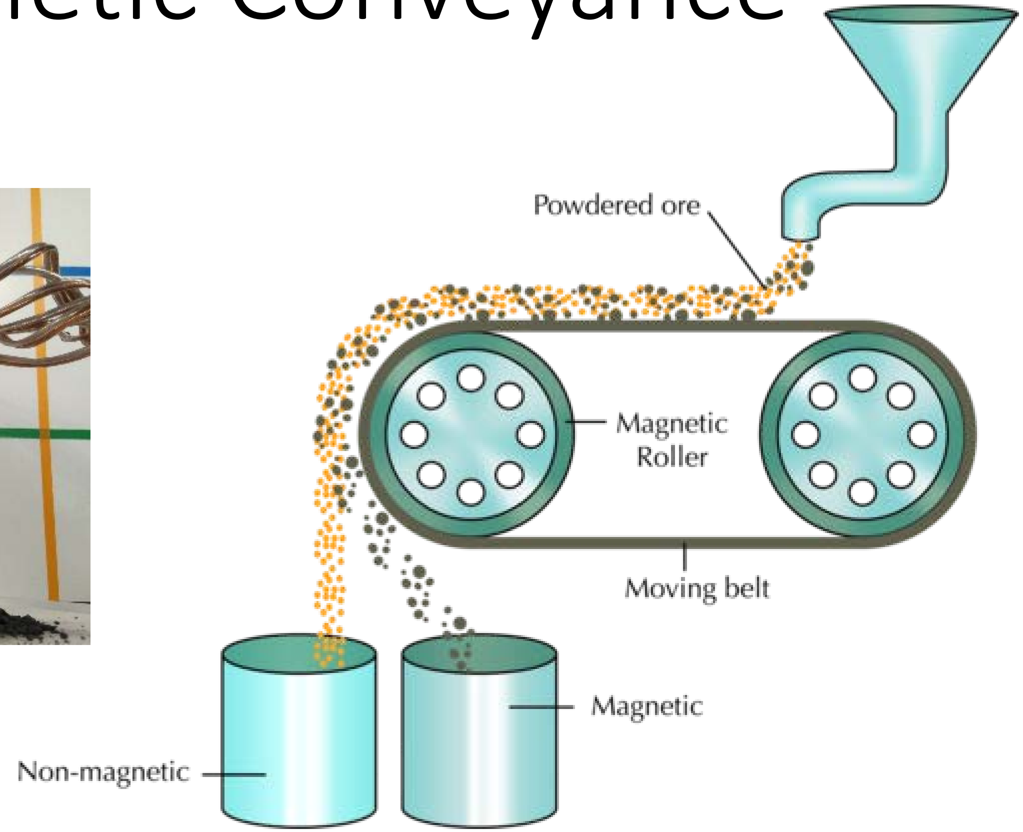
Traverse Method

- Cyclonic Separation
- Loading of Samples
- Gas re-use

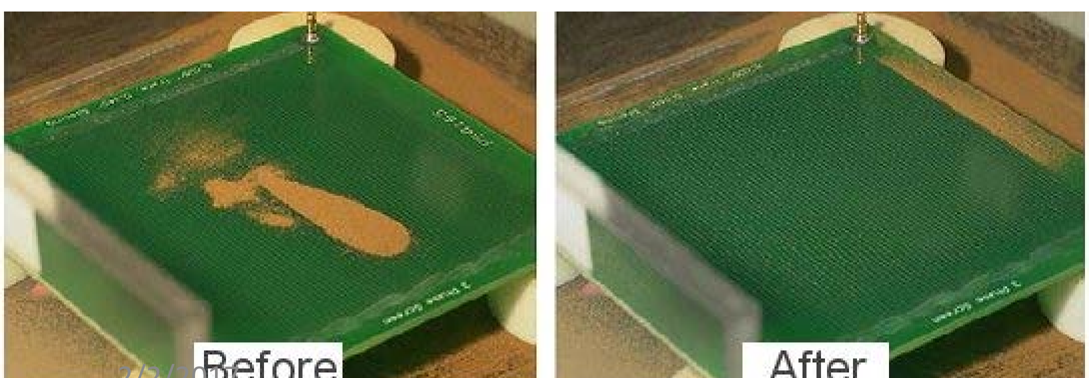


Magnetic Conveyance

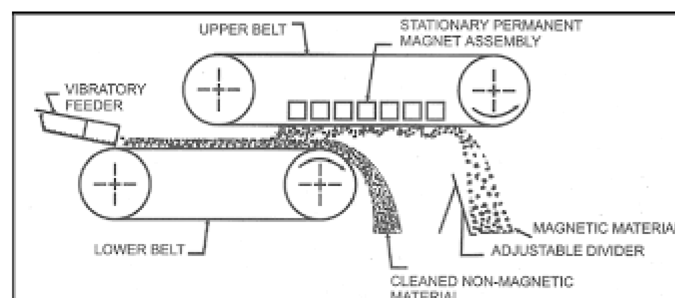
Stephen Covey, Deep Space Industries



http://www.mstworkbooks.co.za/natural-sciences/gr7/gr7-mm-02.html



Nasa KSC



http://www.jupitermagnetics.com/

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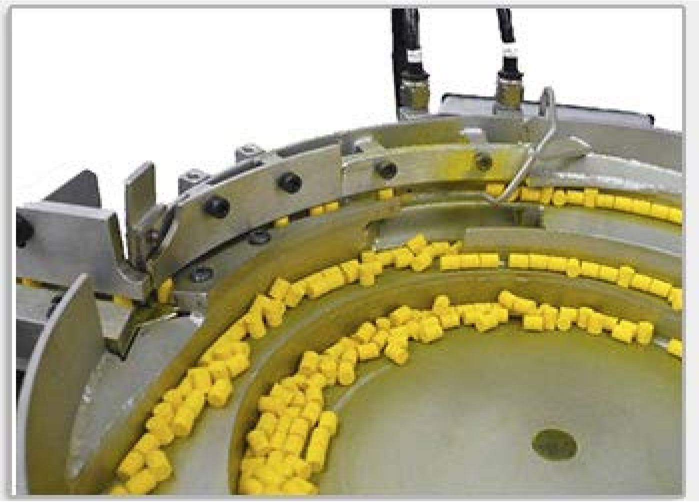
Vibratory Conveyors

http://www.progressindustries.com/products/vibcon.html



http://performancefeeders.com/custom-applications/vibratory-feeder-bowl-system-with-center-discharge

https://www.generalkinematics.com/product/syncro-coil-vibrating-conveyors/

- Few Moving Parts
- Energy Intensive
- Used in various industries

Belt Conveyors

A belt conveyor is a rubber or textile structure with a belt shape closed ring, with a vulcanized or metallic joint, used for material transportation.

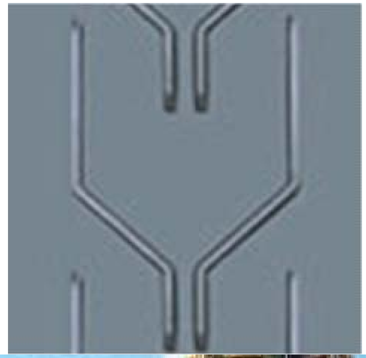
- Belt conveyors are the most used for transporting solid objects and bulk materials at great speeds, covering great distances (up to 30 km)

Phoenix Conveyor Belts

U-cleats and V-cleats profiles

- Designed for transport of all type of bulk material such as rock, sand and gravel. It is also suitable for material in sacks or bags. They allow transport up to 45º from horizontal.



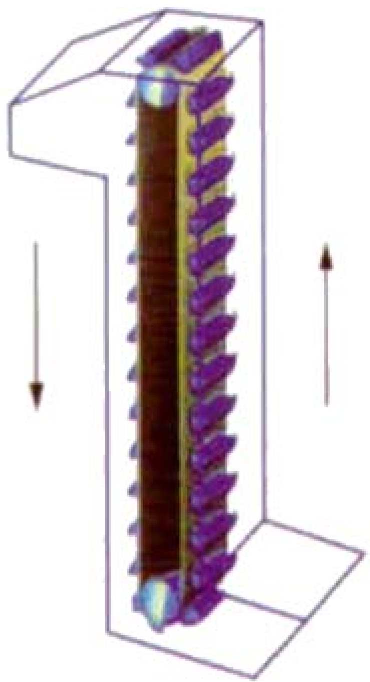


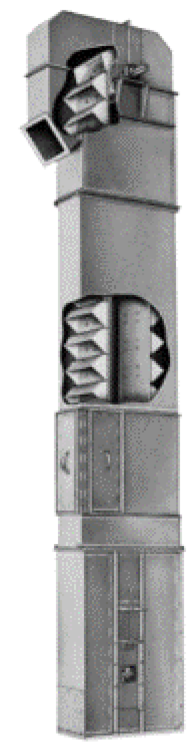
Corrugated edge belt

- Designed for longitudinal transport with a great inclination and vertical, of a wide range of materials, from fine, free flowing grain to coarse-grained limestone. Capacity from 1 m^3/h to 5.000 t/h.

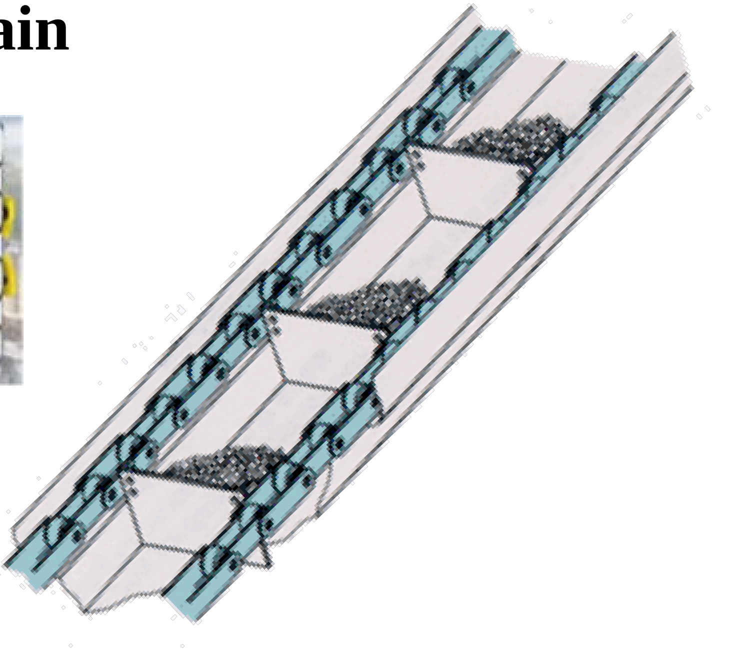
Bucket Elevators

- Bucket elevators are the most common systems used for vertical transport of bulk, dry, wet and even liquid materials.
  - Chain
  - Belt



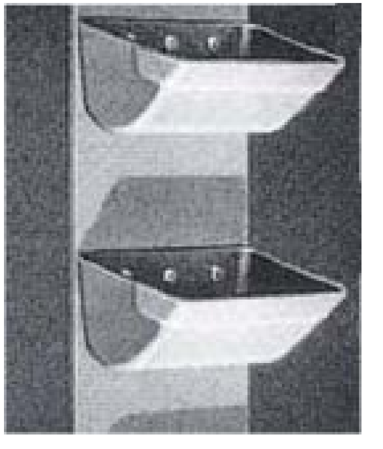


Chain



- Advantages:
  - Higher heights
  - Heavier loads
  - Higher temperatures
- Drawbacks:
  - Speeds up to 1.25 m/s

Belt



- Advantages:
  - Less wear.
  - Silence operation.
  - High specific transport capacity.
  - Lower energy consumption.
  - The most appropriate to manipulate flour, coal, etc.
  - High travel speeds (up to 2.5 m/s).

Cable Cars & Slurry Lines

- Cable cars
- Slurry lines

http://www.aggbusiness.com/sections/quarry-profiles-reports/features/talc-quarry-focusses-on-product-quality/

http://www.dredgingtoday.com/2012/04/13/australia-slurry-pipes-launch-new-uhmwpe-pipe-for-dredging-applications/

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Loaders and Trucks

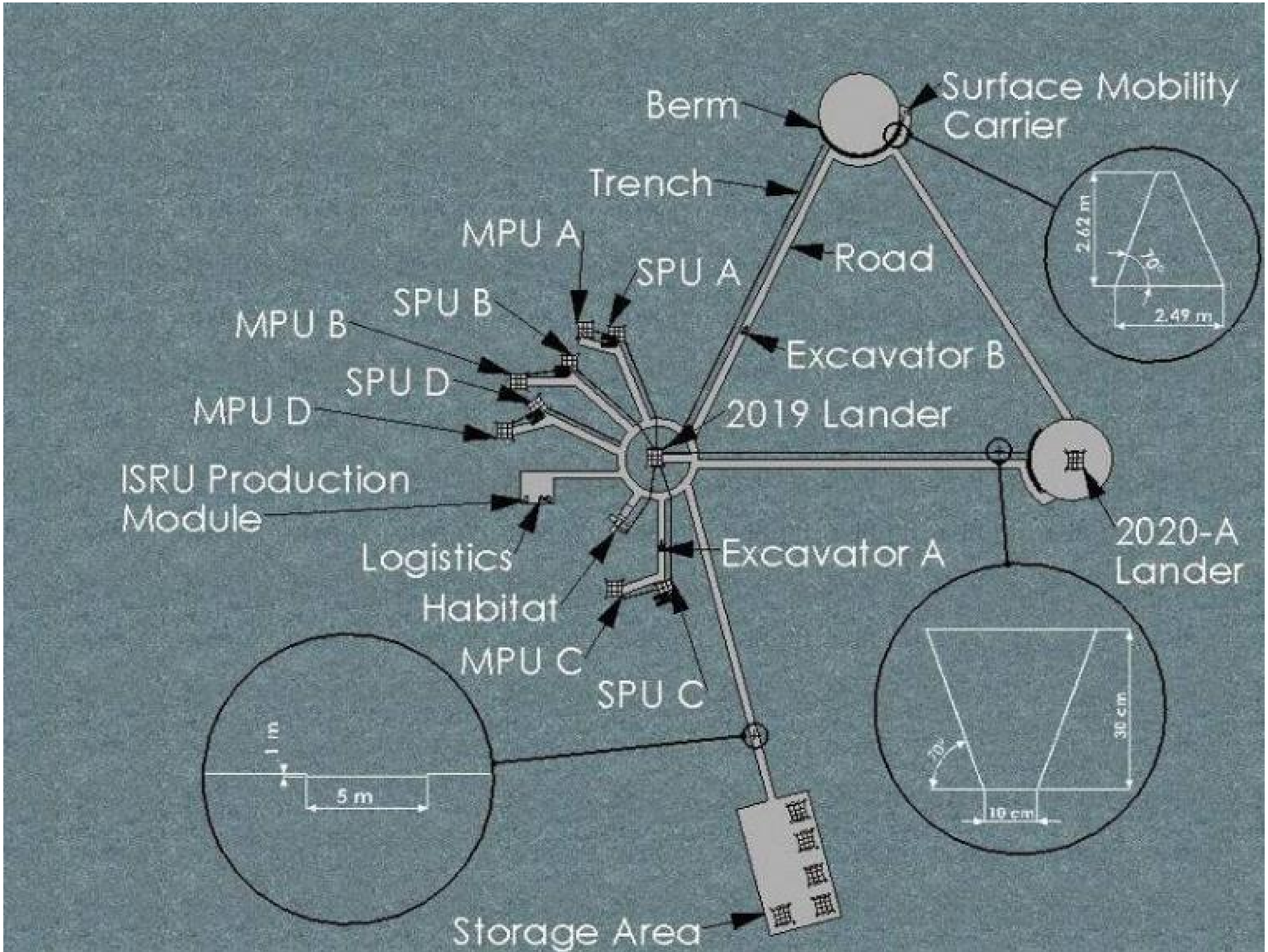
www.cat.com

Michigan Technological University 1885

Mining Requirements

- Mining requirements:
  - How much mining must occur per day or year to meet the outpost needs
    - Water
    - Rocket propellant
    - Feedstock for 3D printing and other manufacturing processes
    - Civil engineering tasks for infrastructure
  - Determining robot size and design for environment
  - Determining how many mining cycles per day/week.
  - Energy needs for mining, etc.

Concept: Lunar Base Layout



Criteria for Lunar Outpost Excavation, R. P. Mueller and R. H. King, Space Resources Roundtable, 2007

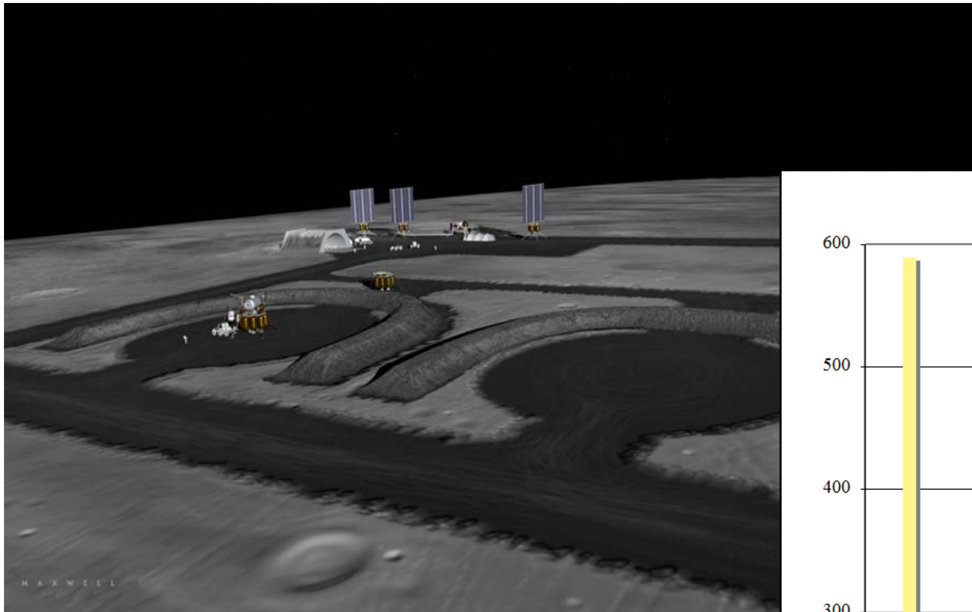
Planetary Surface Construction Tasks

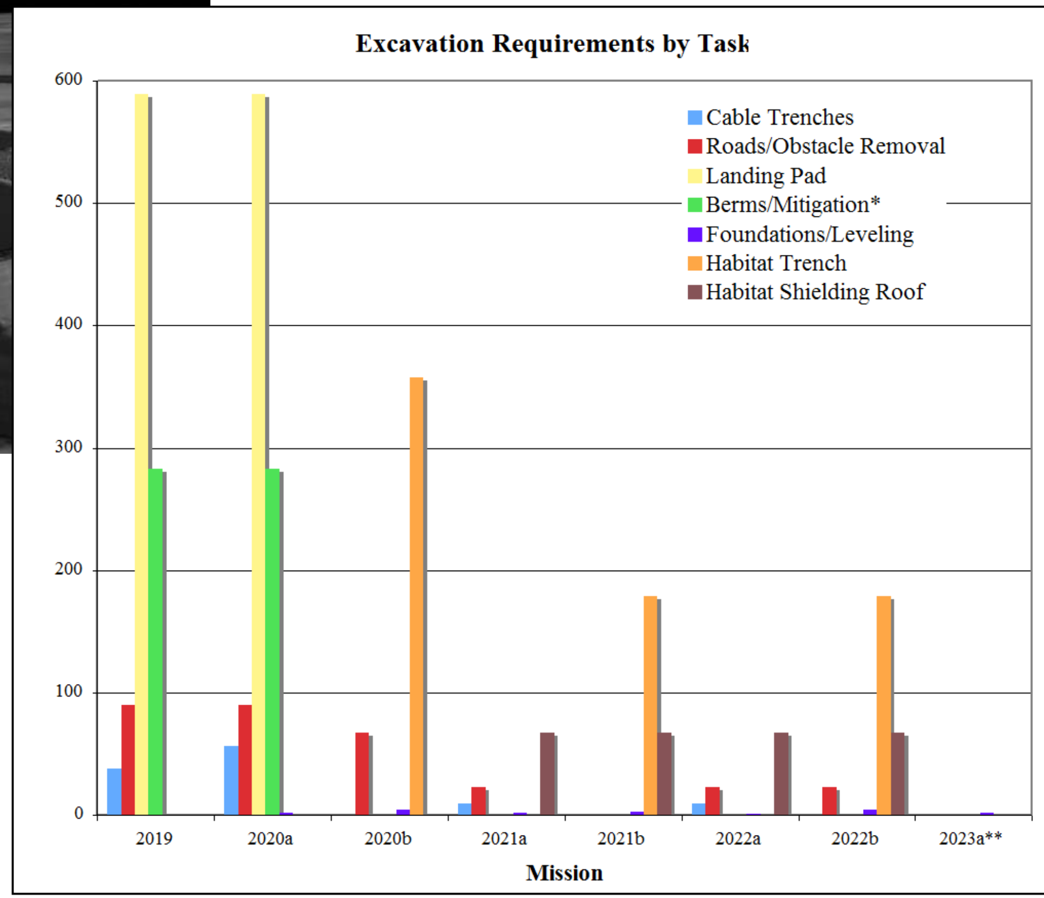
- Launch/Landing Pads
- Beacon/Navigation Aids
- Lighting Systems
- Communications Antenna Towers
- Blast Protection Berms
- Perimeter Pad Access & Utility Roads
- Spacecraft Refueling Infrastructure
- Power Systems
- Radiation, Thermal & Micro Meteorite Shielding

- Electrical Cable/ Utilities Trenches
- Foundations / Leveling
- Trenches for Habitat & Element Burial
- Regolith Shielding on Roof over Trenches
- Equipment Shelters
- Maintenance Hangars
- Dust free zones
- Thermal Wadi's for night time
-
- Regolith Mining for O2 Production
- H2O Ice/Regolith Mining from Shadowed Craters

Lunar Surface Construction Tasks

Criteria for Lunar Outpost Excavation
R. P. Mueller and R. H. King
Space Resources Roundtable –SRR IX
October 26, 2007
Golden, Colorado





SUMMARY	
Task	**%**
Trenching	**4**
Clearing and Compacting	**48**
Building Berms	**18**
Habitat Shielding	**31**
	100
Ice Mining	**17**
Regolith Mining	**83**
Construction	**84**
Mining	**16**

Evolvable MarsvCampaign (EMC)

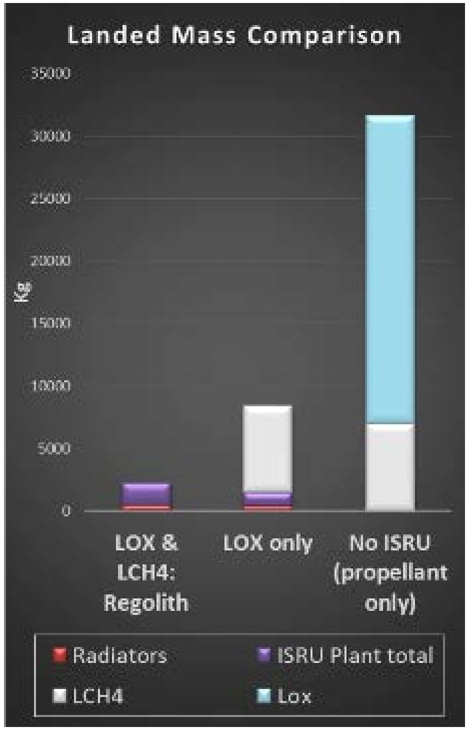
The Potential Benefit of Acquiring Local Water (1 of 2)

	ISRU system **Landed Mass Comparison** (ISRU Hardware + Propellant from Earth)	
	The ISRU system leverages the power and radiator systems that are pre-positioned by the lander for human systems. So these are not explicitly part of the ISRU system.	
	Total Mass, mt	Ratio: Propellant produced per kg of landed mass
ISRU for LOX & LCH_4: Sulfates	1.6	22.1
ISRU for LOX & LCH_4: Regolith	1.7	20.5
ISRU for LOX only (no water)	8.0 (1mt hardware + 7mt Methane)	3.1
Propellant only (no ISRU)	31.6 (24mt Oxygen + 7mt Methane)	na

These comparisons consider ISRU end-to-end systems encompassing excavation, resource processing and propellant production, cleanup, and liquefaction.

For the LOX-only ISRU case, methane would have to be delivered to Mars from Earth.

These calculations only account for the mass of the propellant that is needed in the MAV. They do not account for the additional propellant mass which would be required to deliver that MAV propellant to Mars from LEO. Thus the advantage of a combined ISRU LOX/Methane production system would be greater than indicated.



Harnessing even the lowest yield Mars regolith water resource for ISRU would offer a 6x improvement over an LOX-only ISRU in the terms of the mass of propellant generated for each kg of total ISRU system mass.

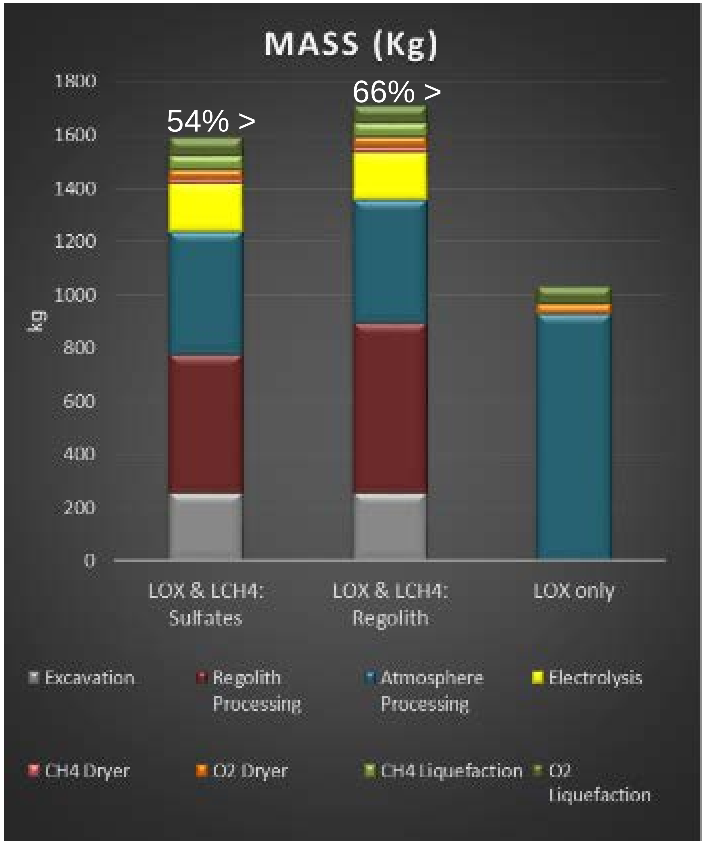
For every kg of total ISRU system mass delivered to Mars:

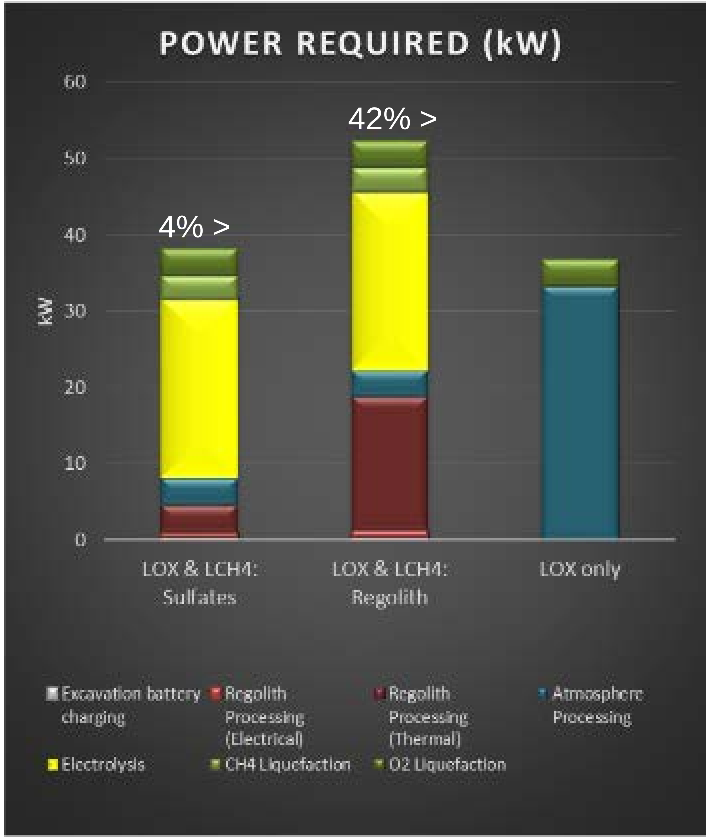
- A Lox/LCH_4 ISRU system can produce 20 kg of propellant
- A Lox-only ISRU system can produce 3 kg of propellant

EMC

The Potential Benefit of Acquiring Local Water (2 of 2)

- The graph below compares ISRU systems for two different water resources and an ISRU LOX-only (no water) system (which is the current architecture baseline).
  - The masses are for the ISRU hardware only. While the water processing system masses are ~60% greater than the LOX-only case, consider that the latter still requires 7mt of terrestrial Methane each trip
  - The benefit of a higher yield granular resource is a power savings. The power required for case B is comparable to the lox-only ISRU system.





Percentages on the graphs represent comparison to LOX-only ISRU

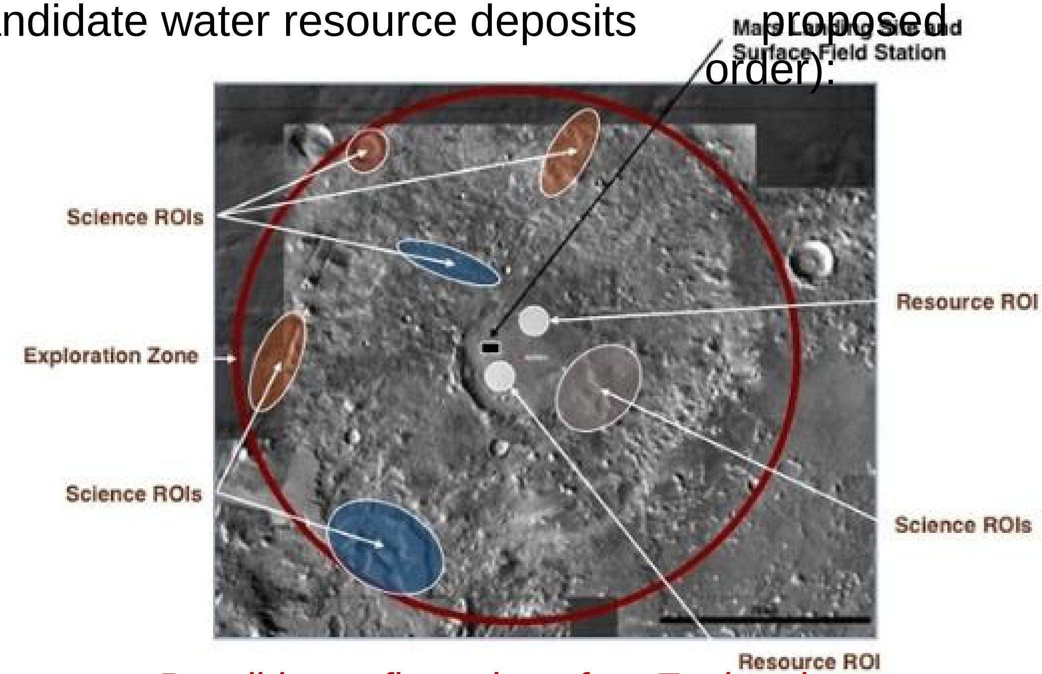
Human Landing Site Selection

- Human Landing Site Selection (HLS[2]): October 2015 workshop on Mars Exploration Zones.
- In addition to science regions of interest, all site proposers were asked to identify one or more candidate water resource deposits within their Exploration Zone that have the potential to produce **5 metric tons** of water per year.
- 47 candidate sites proposed by the world's leading experts in ISRU and Mars geology. The four most common candidate water resource deposits proposed include (not in priority order):

1. Mid-latitude ice
2. Concentrations of poly-hydrated sulfate minerals
3. Concentrations of phyllosilicate minerals
4. Regolith.

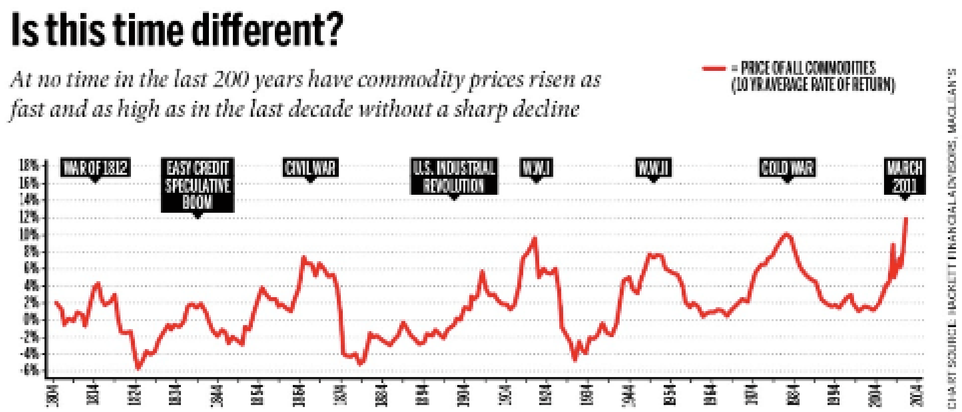
See also ICE-WG (2015; Hoffman and Mueller, co-chairs)

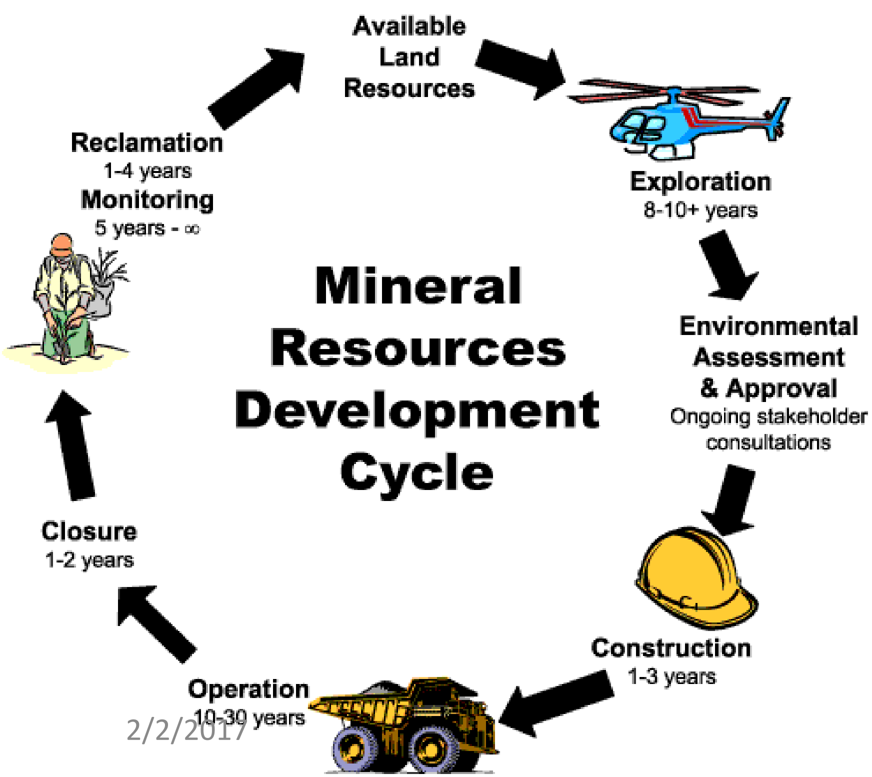
http://www.nasa.gov/journeytomars/mars-exploration-zones



Possible configuration of an Exploration Zone. Note hypothetical "Resource ROIs" in gray.

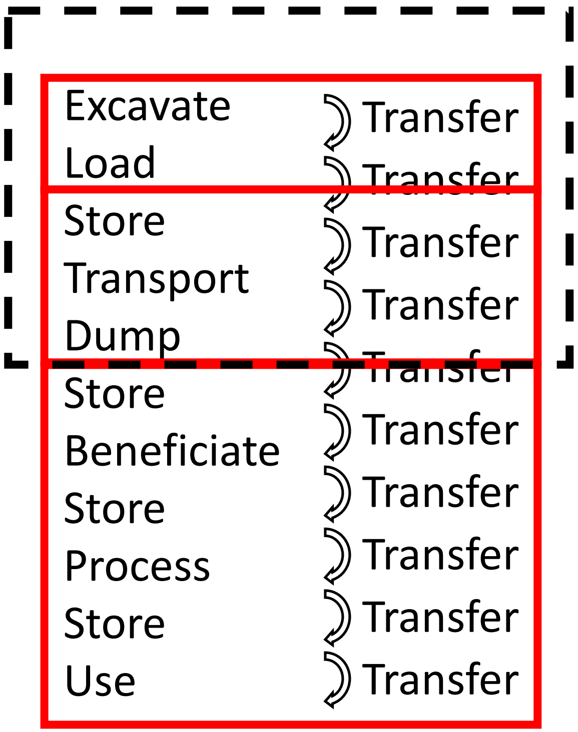
Mining Cycles





Excavate	Transfer
Load	Transfer
Store	Transfer
Transport	Transfer
Dump	Transfer
Store	Transfer
Beneficiate	Transfer
Store	Transfer
Process	Transfer
Store	Transfer
Use	Transfer

Cycles



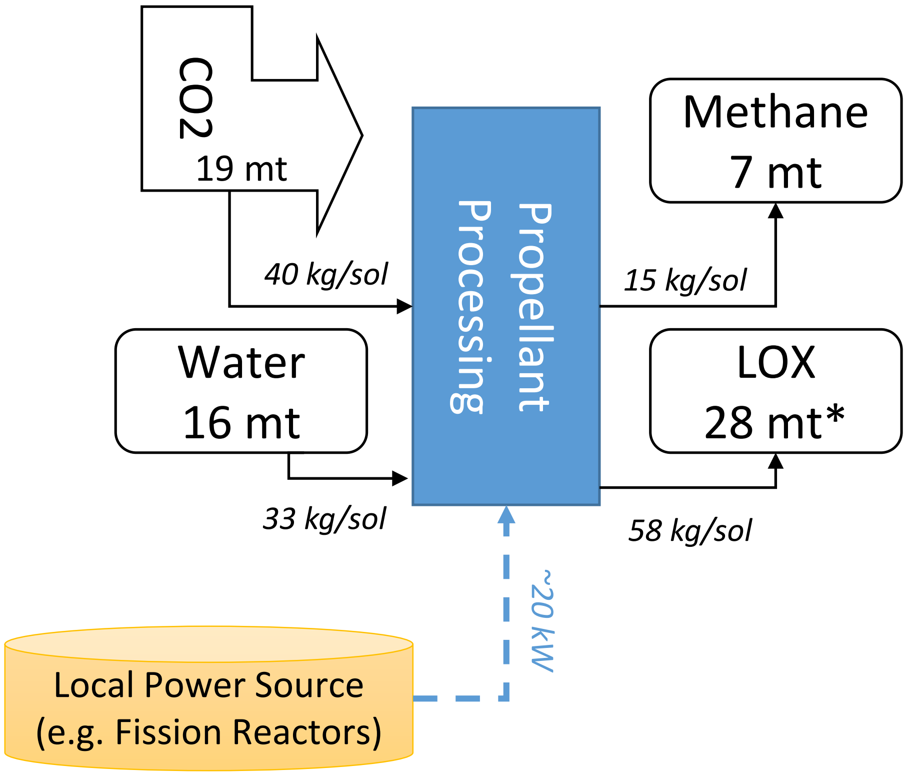
- Different equipment combines different aspects of these. The question is what is the best choice for equipment design for space mining?

  - Determining the correct function per device
  - Determining the correct size of the rover
  - How many trips are needed per day to meet the outpost needs.
  - Is it better to have a larger rover and do one trip or (several) smaller ones with multiple trips?
  - When best to recharge batteries
  - Other uses for the rovers at the outpost need to be worked in schedule

Need System Engineering Approach!

Fuel Processing

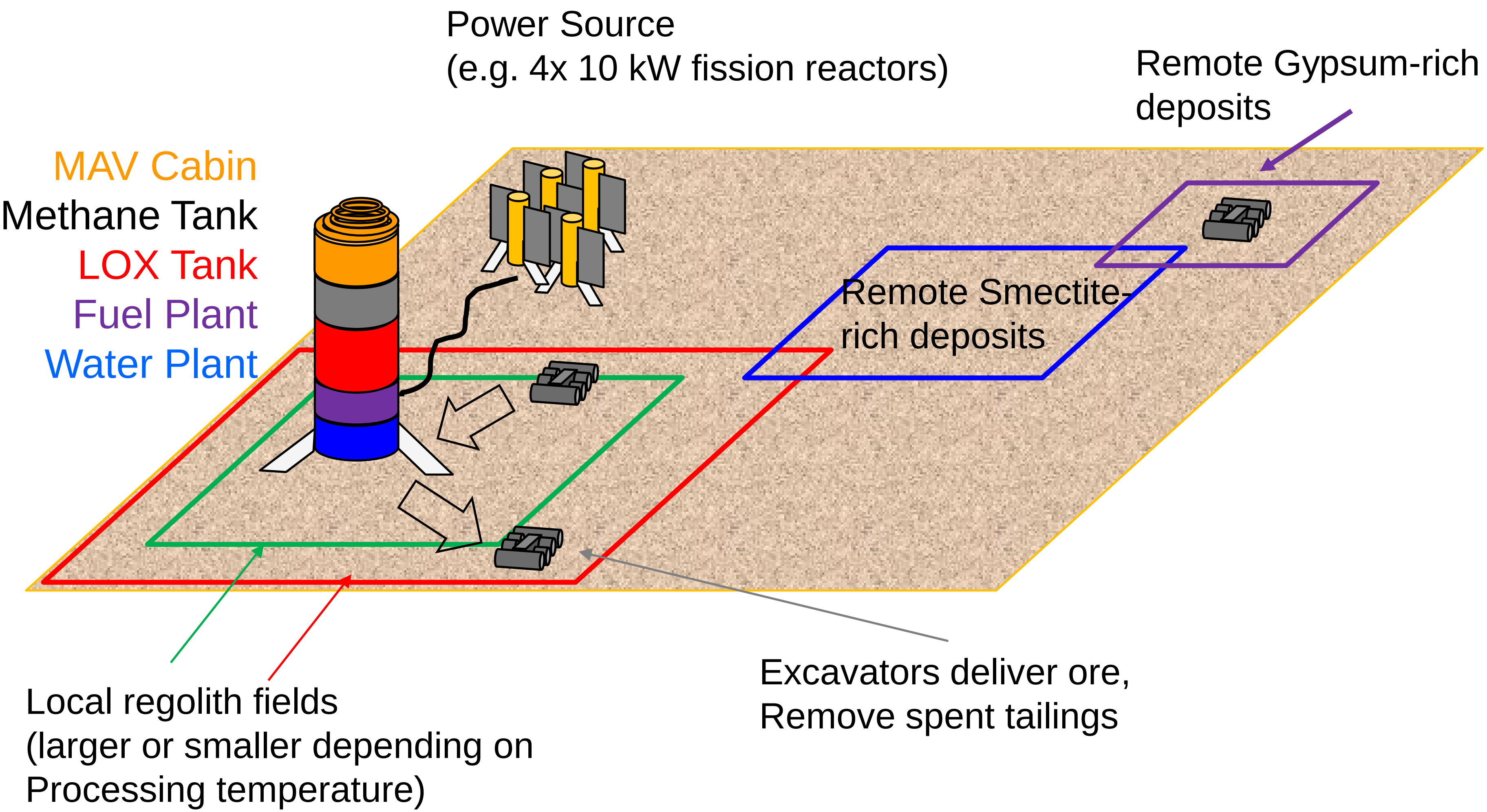
- To generate MAV propellants, total of 16 mt of water would need to be delivered/processed in 480 sols available (33 kg/sol)
- Combines with 19 mt of atmospheric CO_2 to generate Methane & LOX



*Note: only 23 mt required for MAV propellant. Balance available for crew or other uses

Granular Materials Cases:

Pre-deployed ISRU "Enterprise"



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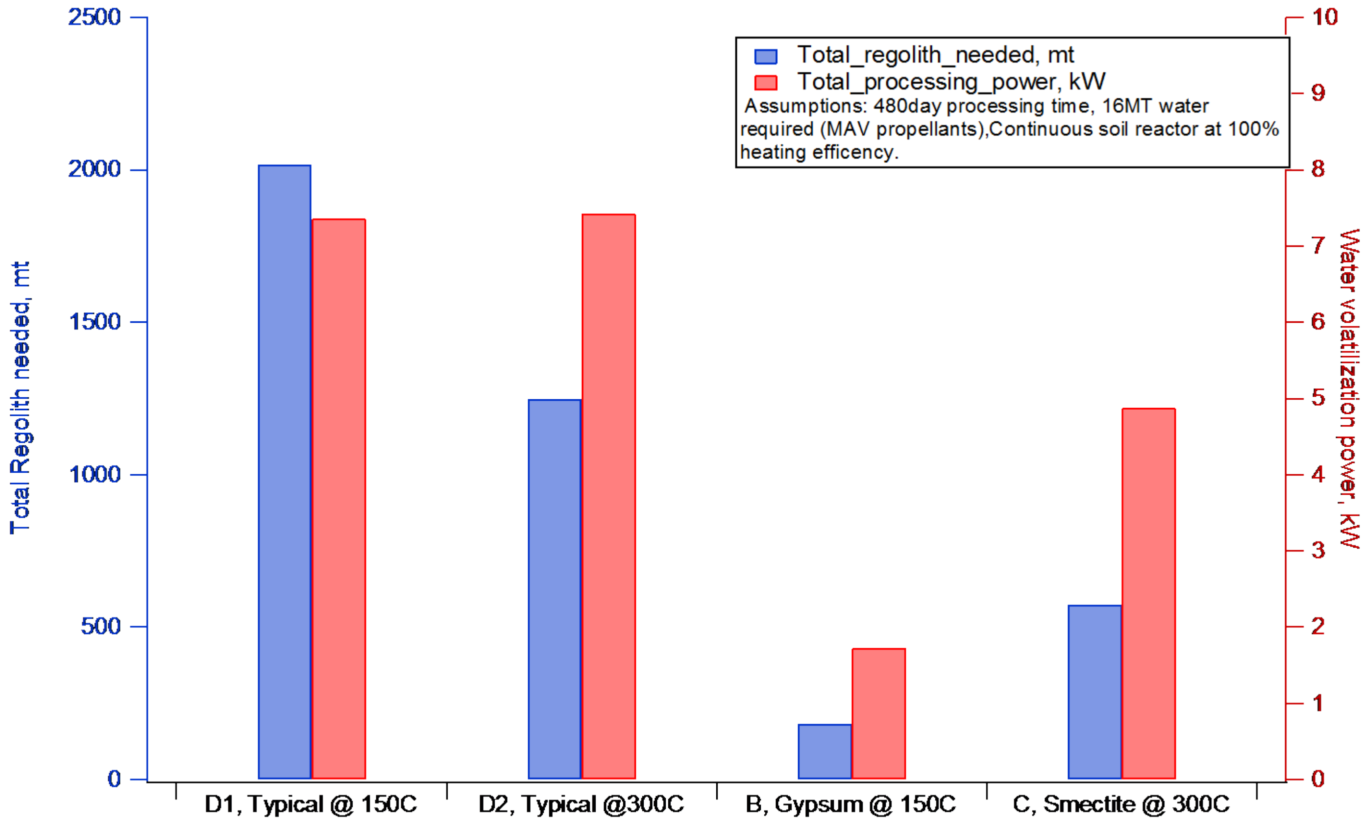
Water Abundances by Feedstock/Temperature

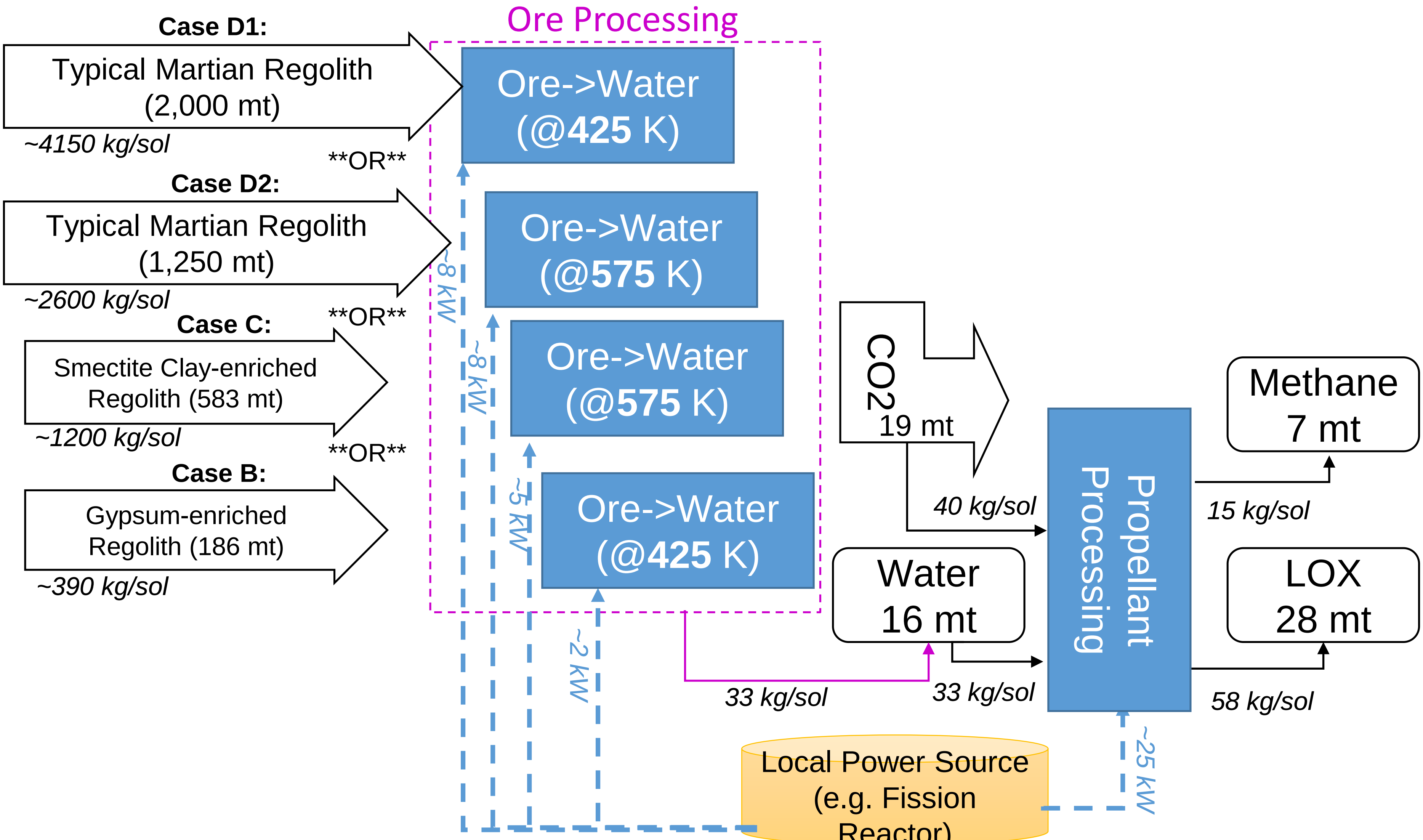
Phase	Characteristic Dehydration Temperature (K)	Assumed Water Content	Gypsum-rich			Smectite-rich			Typical Martian Regolith		
			Case B Assumed Abundance	Case B Potentially Available Water	Case B Cumulative Available Water	Case C Assumed Abundance	Case C Potentially Available Water	Case C Cumulative Available Water	Case D Assumed Abundance	Case D Potentially Available Water	Case D Cumulative Available Water
Allophane	363 K	20%	3%	0.60%	0.60%	3%	0.60%	0.60%	3%	0.60%	0.60%
Bassinite	423 K	6%	0%	0.00%	0.60%	3%	0.18%	0.78%	3%	0.18%	0.78%
Gypsum	423 K	20%	40%	8.00%	**8.60%**	0%	0.00%	0.78%	0%	0.00%	**0.78%**
Akaganeite	523 K	12%	3%	0.36%	8.96%	3%	0.36%	1.14%	3%	0.36%	1.14%
Smectite	573 K	4%	3%	0.12%	9.08%	40%	1.60%	**2.74%**	3%	0.12%	**1.26%**
Basaltic Glass	>750 K	1%	0%	0.00%	9.08%	0%	0.00%	2.74%	23.50%	0.24%	1.50%
"Refractory" (no effective water released)	N/A	0%	51%	0.00%	9.08%	51%	0.00%	2.74%	65%	0.00%	1.50%

Key Characteristics by Feedstock



- Gypsum deposits would have the lowest mass AND power requirements of the granular deposits. Ice mining power not established due to less experience and available data.
- Typical martian regolith processed at low temperatures doesn't result in lower power (due to production rates) AND requires more mass -> NO ADVANTAGE

End-to-end Process Flow



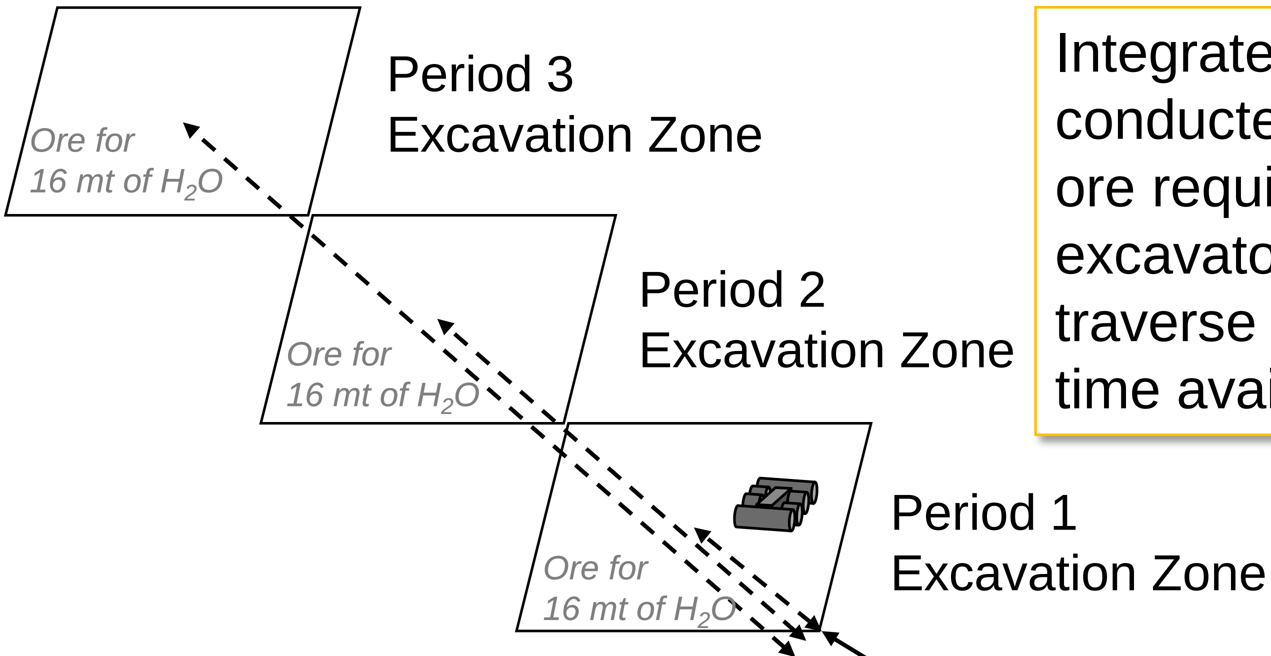
RASSOR Key Characteristics

Baseline hardware design of NASA KSC-developed RASSOR Prototype Excavator - key characteristics of this reference model have been used for preliminary sizing analysis. For additional information about this prototype, contact Rob Mueller.

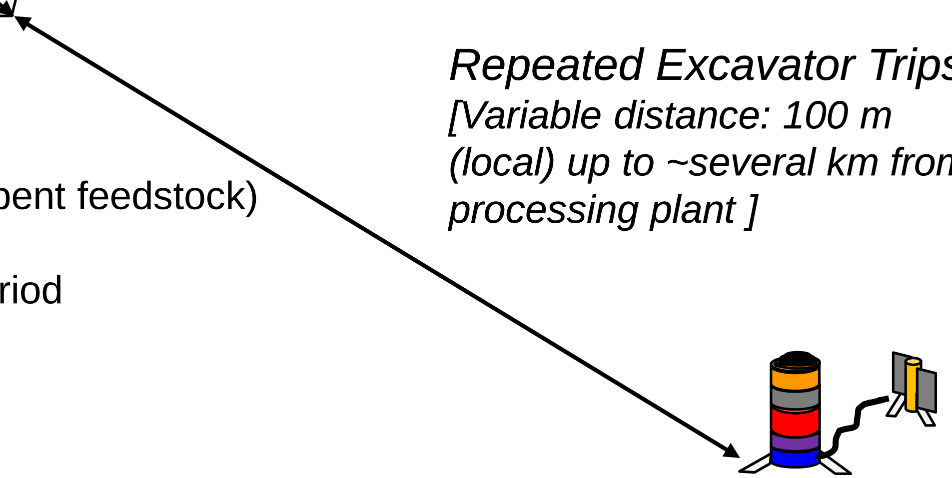
Key Characteristics Assumed:

- Excavator capacity: 2 x 40 kg drums of granular material
- Traverse speed: 25 cm/s
- Battery powered – recharge in proximity to power source
- Duty Cycle / Recharge: 60% on-duty, 40% off-duty [Battery powered – recharge at plant site]

Intro to Excavation/Travel Analysis



Integrated timeline analysis conducted based on amount of ore required, time required for excavator loading/unloading, traverse distances / rates & time available



Each trip excavates and dumps twice (ore & spent feedstock)
24.5 hours operational time / Mars day (Sol)
16 mt of H_2O needed in 480 sol excavation Period
Material is granular uncemented material

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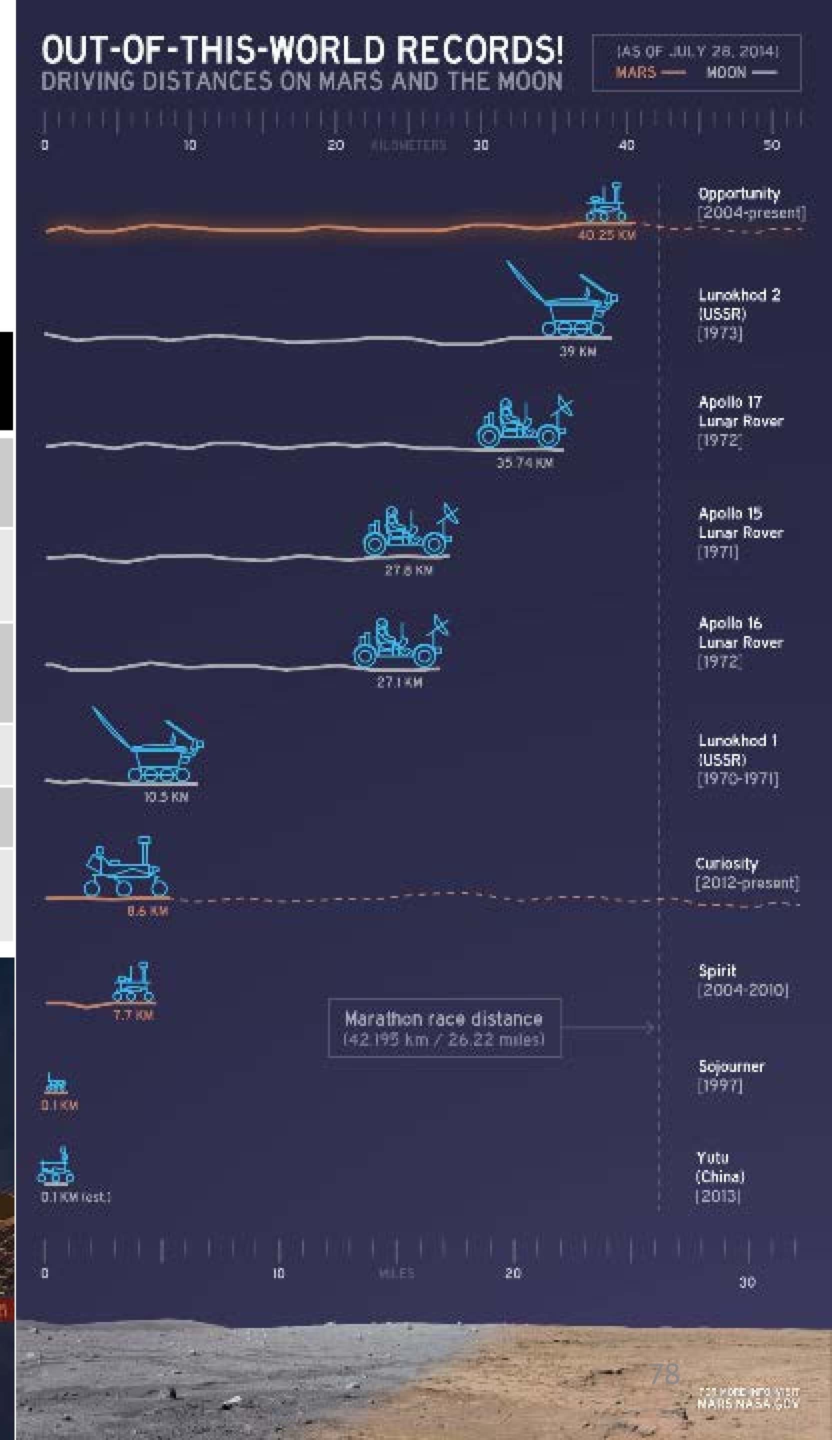
Summary of Excavation/Travel Analysis

Case	Mass of Ore Required (metric tons)	# RASSOR- class loads (@80 kg/load)	Distance from Ore to Plant, typical	# RASSOR – class Excavators used (@ 60% On-Duty)	Duration Required (sols, <480 available)
D1 – Regolith @425K	~2,050 mt	>25,000	~100 m	**3** excavators	382 sols
D2 – Regolith @ 575K	~1,270 mt	>15,800	~100 m	**2** excavators	350 sols
C – Smectite (proximity)	~580 mt	>7,000	~100 m	**1** excavator	318 sols
B - Gypsum	~185 mt	>2,000	**~100 m**	**1** excavator	88 sols
B - Gypsum	(same)	(same)	**~1,200 m**	**1** excavator	480 sols
B - Gypsum	(same)	(same)	**~3,000 m**	**2** excavators	453 sols

- Multiple excavators would be required for typical martian regolith cases (three for D1/two for D2)
- D1 / D2 assumed to be feasible at "any" location (i.e. transportation always ~100m)
- Single excavator could handle hydrated minerals in local proximity
- Smectite would be feasible <100m from lander (318 sols), distances >100m would require >1 excavator
- Pair of rovers could handle gypsum at distances of up to 3 km (same as D2 in local proximity to plant)

Travel Perspective

Case	# RASSOR-class loads (@80 kg/load)	Distance from Ore to Plant, typical	# RASSOR – class Excavators used (@ 60% On-Duty)	Travel Distance (km in 480 sols)
D1 – Regolith @425K	>25,000	~100 m	**3** excavators	5,000 (3) [1,667 (1)]
D2 – Regolith @ 575K	>15,800	~100 m	**2** excavators	3,160 (2) [1,580 (1)]
C – Smectite (proximity)	>7,000	~100 m	**1** excavator	1,400
B - Gypsum	>2,000	**~100 m**	**1** excavator	400
B - Gypsum	(same)	**~1,200 m**	**1** excavator	4,800
B - Gypsum	(same)	**~3,000 m**	**2** excavators	12,000 (2) [6,000 (1)]



Cycle Analysis

Rassor 2.0 excavator use

	Case B	Case C	Case D	
Feedstock per 480 days for 16 MT water	186,047	583,942	2,051,282	kg
Number of excavators	1	1	1	integer
Effective dutycycle	40%	40%	40%	percent
Excavation rate	1,000	1,000	1,000	kg/hr
travel speed	0.26	0.26	0.26	m/s
hopper size	80	80	80	kg
excavation depth	0.05	0.05	0.05	m
Bulk density	2	2	2	g/cm3
Total Excavator Mass	240	240	240	kg
Return trips per excavator to acquire feedstock	2,326	7,300	25,642	trips/480
size of square for 1 time period production volume	43.1	76.4	143.2	m
	4.8458	15.208	53.42083	

Threshold **480** days

Case B Number of days (of 24.5 hours) to gather required feedstock

Distance (m)	100	200	300	400	500	600	700	800	900	1000	2000	3000	4000	5000
Period 1	88.2	116.6	145.0	173.4	201.8	230.2	258.6	287.0	315.4	343.8	627.8	911.7	1,195.7	1,479.6
Period 2	105.6	134.0	162.4	190.7	219.1	247.5	275.9	304.3	332.7	361.1	645.1	929.0	1,213.0	1,496.9
Period 3	122.9	151.3	179.7	208.1	236.5	264.9	293.3	321.7	350.0	378.4	662.4	946.4	1,230.3	1,514.3
Period 4	140.2	168.6	197.0	225.4	253.8	282.2	310.6	339.0	367.4	395.8	679.7	963.7	1,247.6	1,531.6

Case C Number of days (of 24.5 hours) to gather required feedstock

Distance (m)	100	200	300	400	500	600	700	800	900	1000	2000	3000	4000	5000
Period 1	318.9	408.0	497.2	586.3	675.4	764.5	853.7	942.8	1,031.9	1,121.0	2,012.3	2,903.5	3,794.8	4,686.0
Period 2	415.2	504.4	593.5	682.6	771.7	860.8	950.0	1,039.1	1,128.2	1,217.3	2,108.6	2,999.8	3,891.1	4,782.3
Period 3	511.5	600.7	689.8	778.9	868.0	957.2	1,046.3	1,135.4	1,224.5	1,313.7	2,204.9	3,096.1	3,987.4	4,878.6
Period 4	607.9	697.0	786.1	875.2	964.4	1,053.5	1,142.6	1,231.7	1,320.9	1,410.0	2,301.2	3,192.5	4,083.7	4,974.9

Case D Number of days (of 24.5 hours) to gather required feedstock

Distance (m)	100	200	300	400	500	600	700	800	900	1000	2000	3000	4000	5000
Period 1	1,416.1	1,729.2	2,042.2	2,355.3	2,668.4	2,981.5	3,294.5	3,607.6	3,920.7	4,233.8	7,364.5	10,495.3	13,626.1	16,756.9
Period 2	2,050.2	2,363.3	2,676.4	2,989.4	3,302.5	3,615.6	3,928.7	4,241.7	4,554.8	4,867.9	7,998.7	11,129.4	14,260.2	17,391.0
Period 3	2,684.3	2,997.4	3,310.5	3,623.6	3,936.6	4,249.7	4,562.8	4,875.9	5,189.0	5,502.0	8,632.8	11,763.6	14,894.3	18,025.1
Period 4	3,318.5	3,631.5	3,944.6	4,257.7	4,570.8	4,883.9	5,196.9	5,510.0	5,823.1	6,136.2	9,266.9	12,397.7	15,528.5	18,659.3

Cutoff **10** **Percent excavation time of trip**

Case B Percent Excavation vs Total return trip time

Distance	100	200	300	400	500	600	700	800	900	1000	2000	3000	4000	5000
year 1	12.0	9.1	7.3	6.1	5.3	4.6	4.1	3.7	3.4	3.1	1.7	1.2	0.9	0.7
year 2	10.1	7.9	6.5	5.6	4.9	4.3	3.9	3.5	3.2	2.9	1.6	1.1	0.9	0.7
year 3	8.7	7.0	5.9	5.1	4.5	4.0	3.6	3.3	3.0	2.8	1.6	1.1	0.9	0.7
year 4	7.6	6.3	5.4	4.7	4.2	3.8	3.4	3.1	2.9	2.7	1.6	1.1	0.9	0.7

Case C Percent Excavation vs Total return trip time

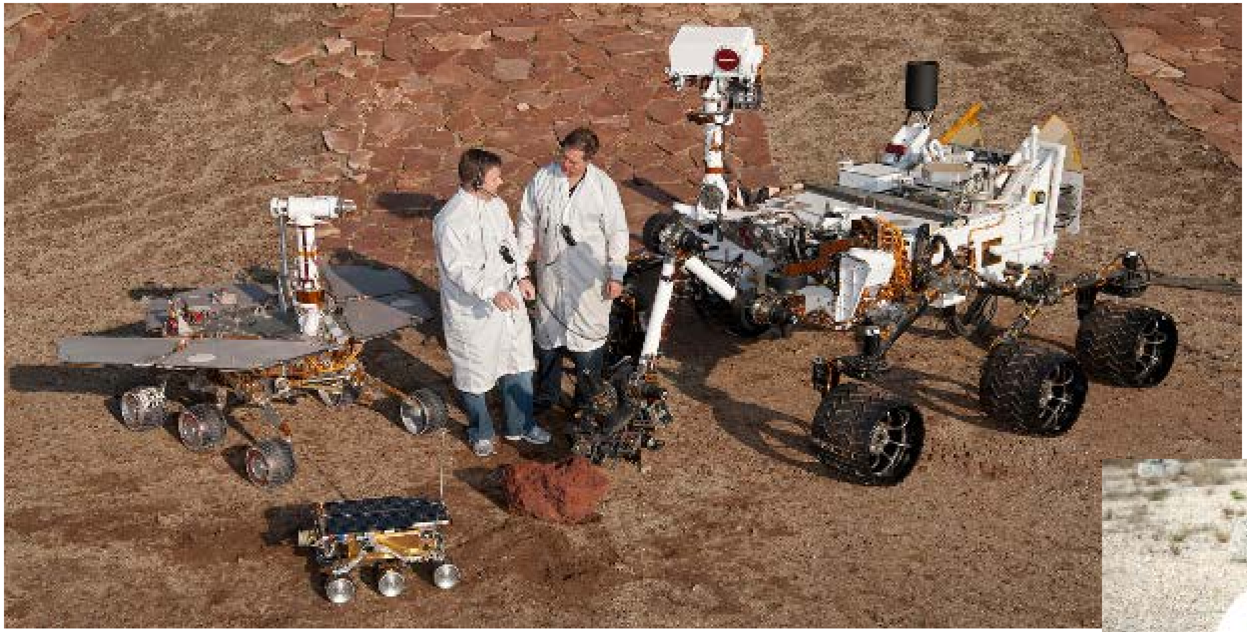
Distance	100	200	300	400	500	600	700	800	900	1000	2000	3000	4000	5000
year 1	10.5	8.2	6.7	5.7	4.9	4.4	3.9	3.5	3.2	3.0	1.7	1.1	0.9	0.7
year 2	8.0	6.6	5.6	4.9	4.3	3.9	3.5	3.2	3.0	2.7	1.6	1.1	0.9	0.7
year 3	6.5	5.6	4.8	4.3	3.8	3.5	3.2	2.9	2.7	2.5	1.5	1.1	0.8	0.7
year 4	5.5	4.8	4.2	3.8	3.5	3.2	2.9	2.7	2.5	2.4	1.5	1.0	0.8	0.7

Case D Percent Excavation vs Total return trip time

Distance	100	200	300	400	500	600	700	800	900	1000	2000	3000	4000	5000
year 1	8.3	6.8	5.7	5.0	4.4	3.9	3.6	3.2	3.0	2.8	1.6	1.1	0.9	0.7
year 2	5.7	5.0	4.4	3.9	3.5	3.2	3.0	2.8	2.6	2.4	1.5	1.1	0.8	0.7
year 3	4.4	3.9	3.5	3.2	3.0	2.8	2.6	2.4	2.3	2.1	1.4	1.0	0.8	0.7
year 4	3.5	3.2	3.0	2.8	2.6	2.4	2.3	2.1	2.0	1.9	1.3	0.9	0.8	0.6

- 80 kg batches for processing
- Transfer spent feedstock
- Store products

Sense of Scale



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Questions?

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Exploration

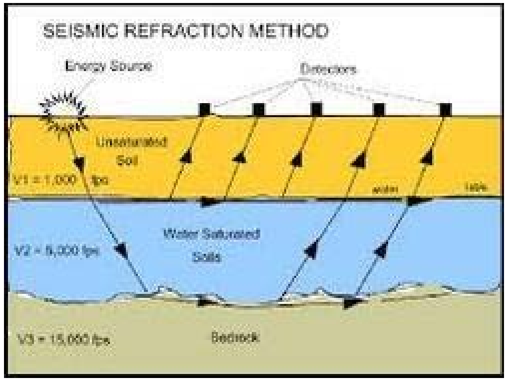
- “Conveying technologies, Mining Cycles and Mining Requirements”
- Several topics will be discussed in this seminar. A crucial first step in any mining operation is exploration of an area or planetary body for resources. This involves orbital, aerial and surface exploration techniques. Design of the mine, engineering, processing and equipment design and system trade-offs are enormously dependent on what the resource and waste mix are as well as the location and chemical and mechanical form it occurs in. More knowledge (risk reduction) is better, but it comes at a price.
- The location of the resource is fixed but the location of the mine, processing facilities, utilities and end product users is not. Conveyance between these places is necessary since it is unlikely these facilities will be in the same place for reasons such as dust production, minimizing transportation energy use, etc. Within a processing facility conveyance is also required from one system to another. Traditional conveyance techniques such as conveyor belts, augers, vibratory conveyance, rail and loaders and trucks will be discussed as well as more specialized methods such as hydraulic, magnetic, gravitic, pneumatic methods.
- Sizing of the components, equipment and processing facilities as well as a batch or continuous process is determined by the conveyance between the different steps. Mining cycles and their efficiency are the driving factor in any Earth mine design in both underground and surface mining. The entire supply chain has several cycles in it that all have to be sized together so there is no over or under capacity along the chain. This includes conveyance time, anticipated break downs, scheduled maintenance, communication delays, recharge time, throughput, buffer supplies, etc. Automation (and the level of autonomy) is of interest to many Earth companies and is a driving requirement for space mining. Typically when equipment stands still, it is losing money, and the maximization of utilization is crucial for profits in Earth’s mining industry. In space mining, instead of pure economy, custom equipment needs to be sized properly to maximize efficiency and minimize mass and power requirements.
- Exploration, Conveyance and Mining Cycles are all determined fundamentally by the mining requirements, or how much feedstock/ore is required per day. Different options may exist to produce the same amount of end-product (e.g. water to produce Oxygen and hydrogen). In addition, other outpost needs require mining / material excavation and transport (roads, berms, landing pads, etc. civil engineering). The total outpost growth and needs over time determine the size, type and number of the mining equipment needed.

- Controlled Source Audio Frequency Magnetotelluric (CSAMT) (sometimes called complex resistivity)
  - Good for contaminants
  - Application for
    - Vein type ore bodies
    - Geothermal prospecting
    - Geologic mapping
- Very Low Frequency EM
  - Source of VLF should be located in direction of target
  - Measure the tilt of the magnetic field
  - Mapping of faults, veins, geologic mapping

Refraction method

- Shoot both directions to identify dip of layers
  - Rule of thumb – 50 ft deep, offset min 5x depth = 250 ft

- Wave changes direction due to change in wavespeed due to change in density or strength of rock it travels through

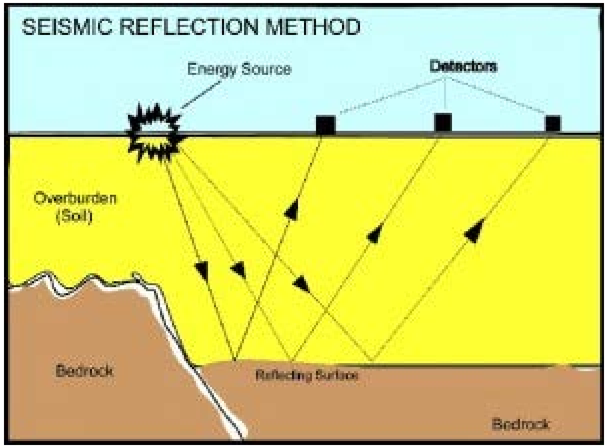


http://www.geologicresources.com/seismic_refraction_method.html

Reflection method

- All about secondary arrivals

- A portion of the energy gets reflected of boundaries between layers



http://www.geologicresources.com/seismic_reflection_method.html

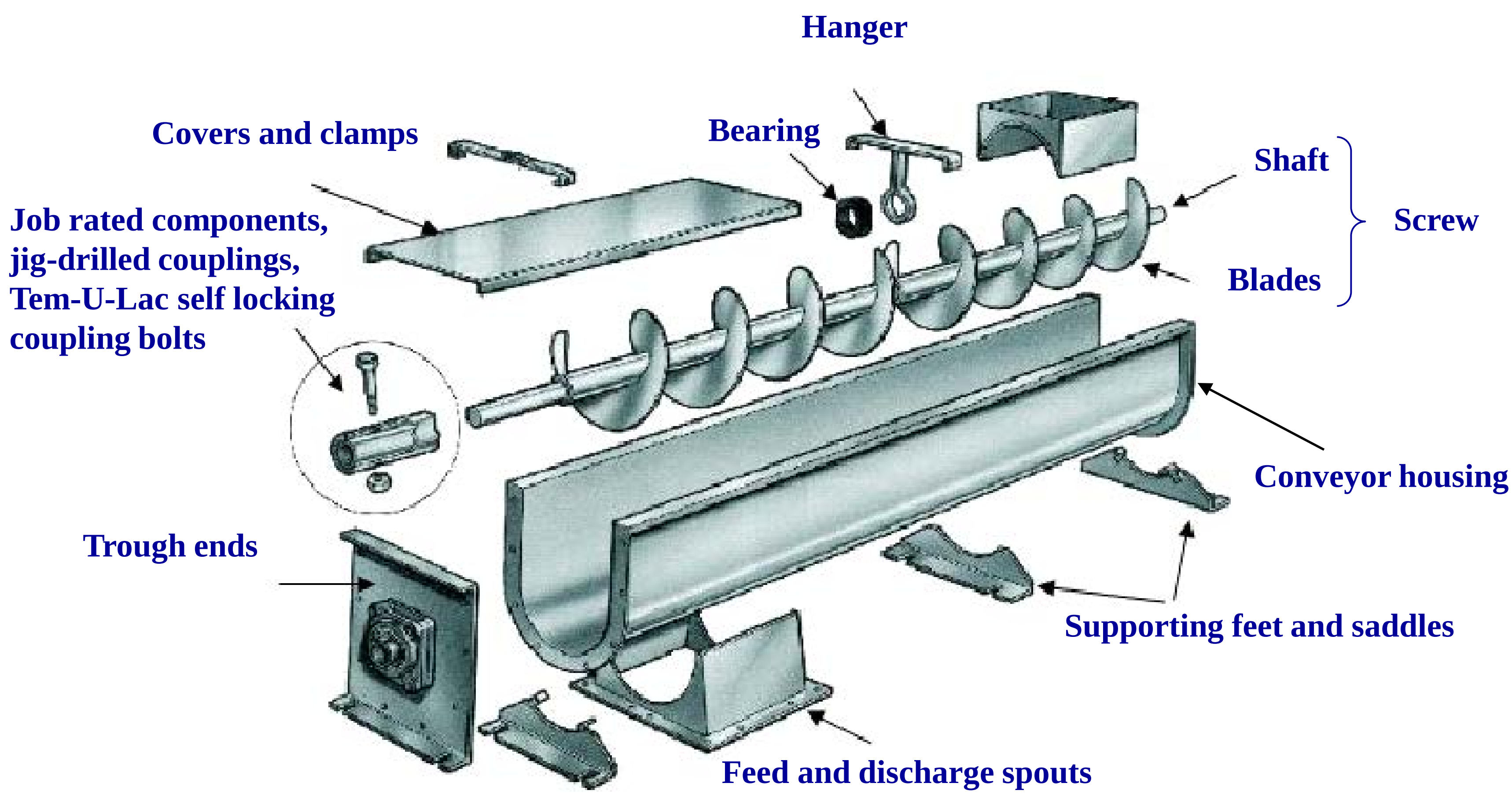
Introduction: Reference Cases

1. Since both sides of the “reserves” interface are incompletely defined (see **Slides #11-13**), the best way to proceed is by defining a set of reference cases, and using them to evaluate the relationships between “discoverability” and “producibility”.
2. The reference cases are all hypothetical—the question we are asking is “if discovered, would these be useful”?
   - The hypothetical cases are based on our current incomplete knowledge of Mars: We perceive there to be reasonable potential that deposits as good as these exist (but discovering and defining them would take work!).
3. Once we understand the thresholds differentiating viable from non-viable, and the parameters that most matter for optimizing the engineered system, the priorities for a logical exploration program can be defined.

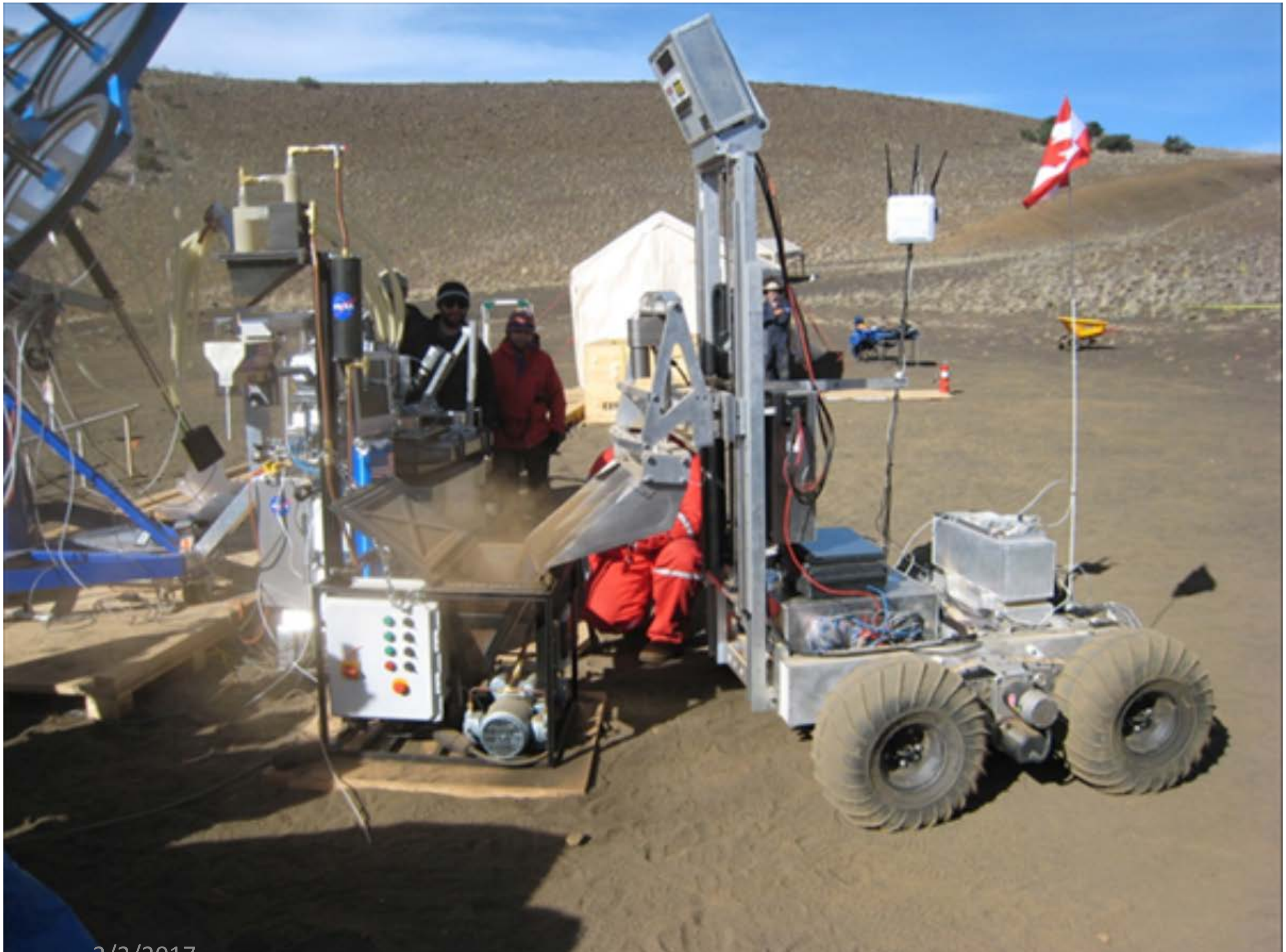
Reference Reserves Notes

1. Assume Case A consists of glacial ice underlying a sublimation lag, but is divided into A1: an ice deposit mined by open pit methods, and A2: an ice deposit mined by down-hole heating/recovery methods. The thickness of this lag is in the 1-10 m range limited by SHARAD measurements (See **Slide #20**.) Future data sets and instruments can improve this precision.
2. For Cases B and C, assume that in a location where bedrock containing high concentrations of these minerals exists, locations can be found where weathering has disaggregated the rock into granular material.
3. The 4 wt% water noted for smectite in Cases B, C and D is the average wt% water in a combination of Na- and Ca- forms; the average water content may be higher for some other types of phyllosilicates (see **Slide #22**).
4. The source data from Case D is explained in detail on **Slides #23-25**. Note that the "water" is inferred to be contained in three phases, two of which dehydrate at 100C, and one of which dehydrates at >500C. We make the assumption (to be reviewed) that material of this quality can be found at most/all candidate landing sites without exploration. Since this material occurs "everywhere", transportation demands would be minimized.
5. Whether deposits better than these reference cases can be discovered and defined is left as an exploration question (see **Slide #62**).

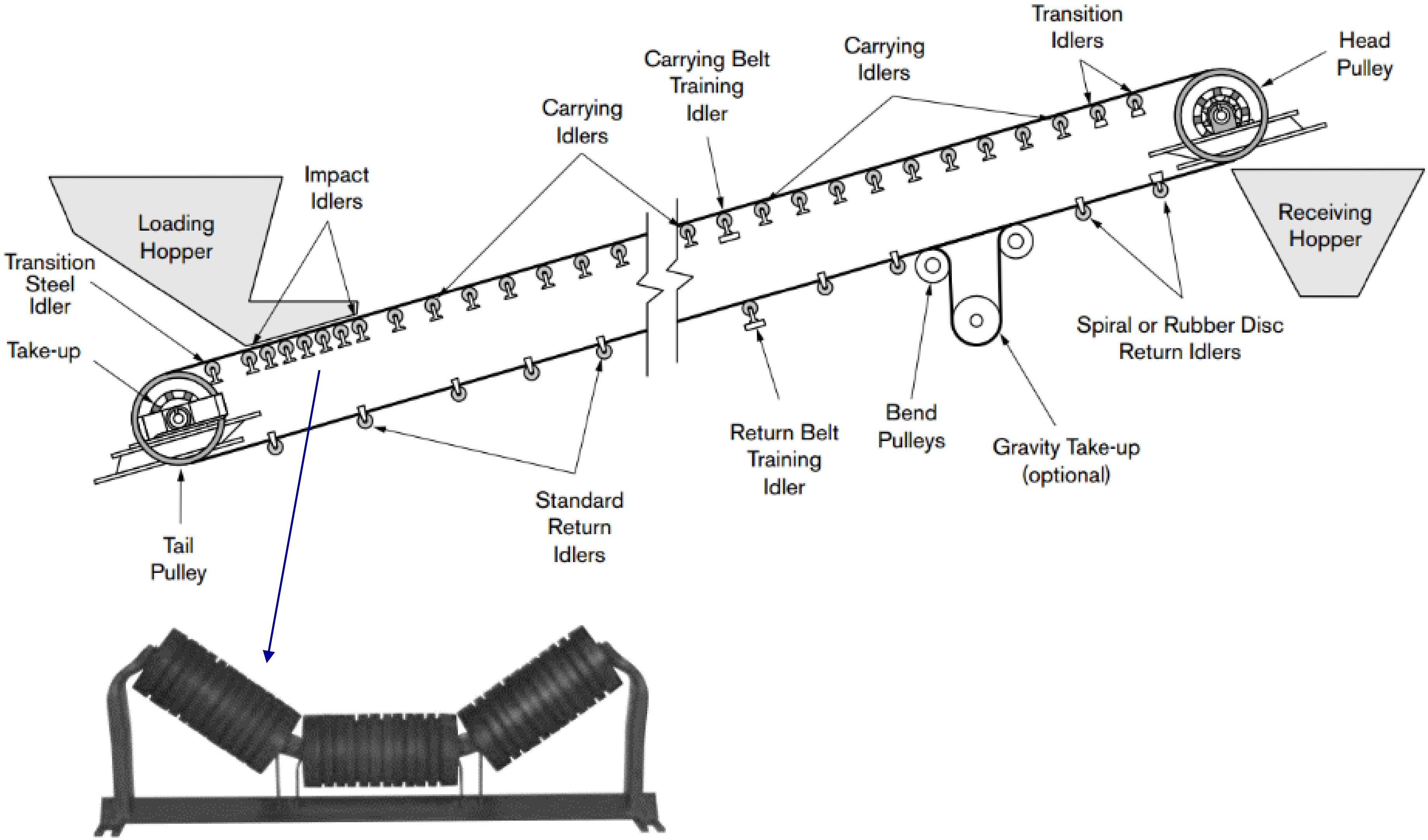
COMPONENTS



Hanger
Covers and clamps
Bearing
Shaft
Screw
Blades
Job rated components,
jig-drilled couplings,
Tem-U-Lac self locking
coupling bolts
Conveyor housing
Trough ends
Supporting feet and saddles
Feed and discharge spouts



COMPONENTS



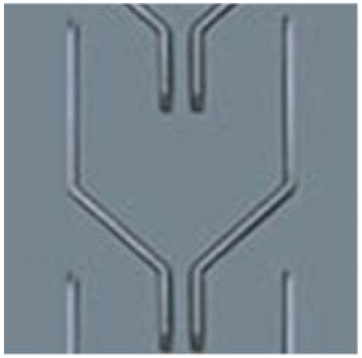
Rex Converyor Idlers Catalog

BELT

Belt conveyors for vertical or inclined transport

U-cleats and V-cleats profiles

- **Designed for transport of all type of bulk material such as rock, sand and gravel. It is also suitable for material in sacks or bags. They allow transport up to 45º over the horizontal.**



BELT

Corrugated edge belt

- Designed for longitudinal transport with a great inclination and vertical, of a wide range of materials, from fine, free flowing grain to coarse-grained limestone. Capacity from 1 m^3/h to 5.000 t/h.

- **It has a:**
  - A bottom belt with a textile longitudinal reinforcement and/or transversal of steel cords.
  - Ondulated lateral walls of reinforced vulcanized rubber (20 – 400 mm).
  - Transversal buckets that avoid material sliding.

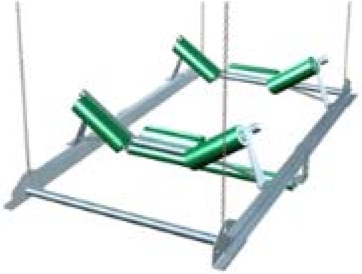
BELT

BELT CONVEYOR STRUCTURE

Support structure of the belt and other components

- Designed to guarantee that the support of the belt is firm and aligned.
- Every component has to be perfectly joined to the structure taking into account their level and angle.
- The joints must not have differences in height and horizontal levelling must be kept.

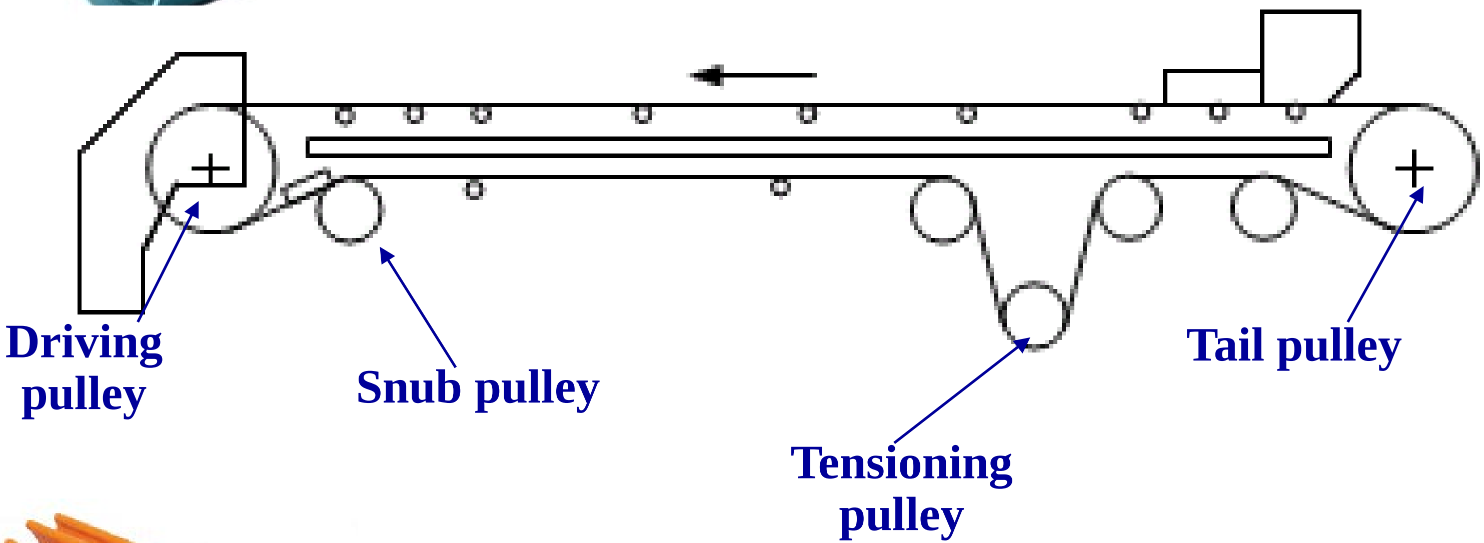
Support structure in the ground with steel beams with U or tubular cross section

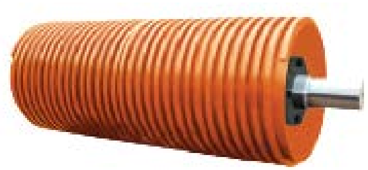


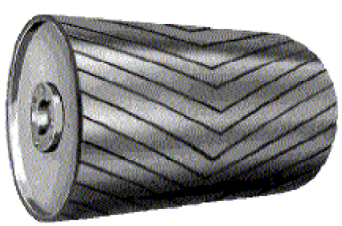
Hanged support structure in the ceiling by means of steel cables

Hybrid support structure

PULLEYS







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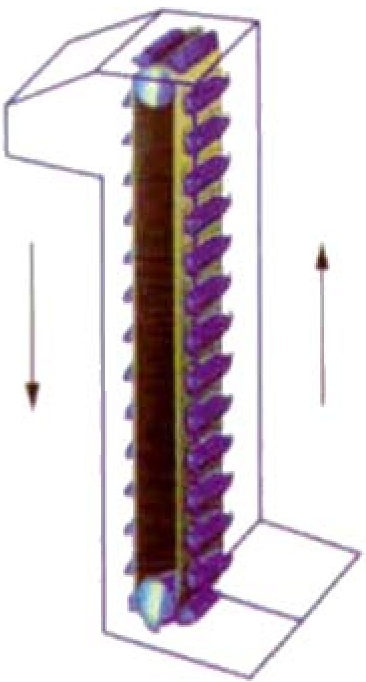
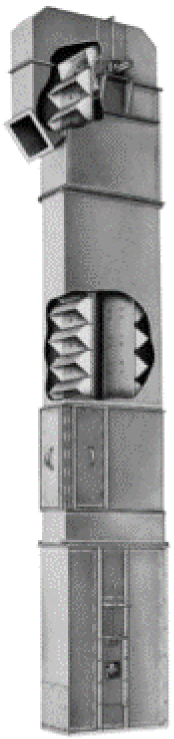
BUCKET ELEVATORS

Bucket elevators are the most common systems used for vertical transport of bulk, dry, wet and even liquid materials.

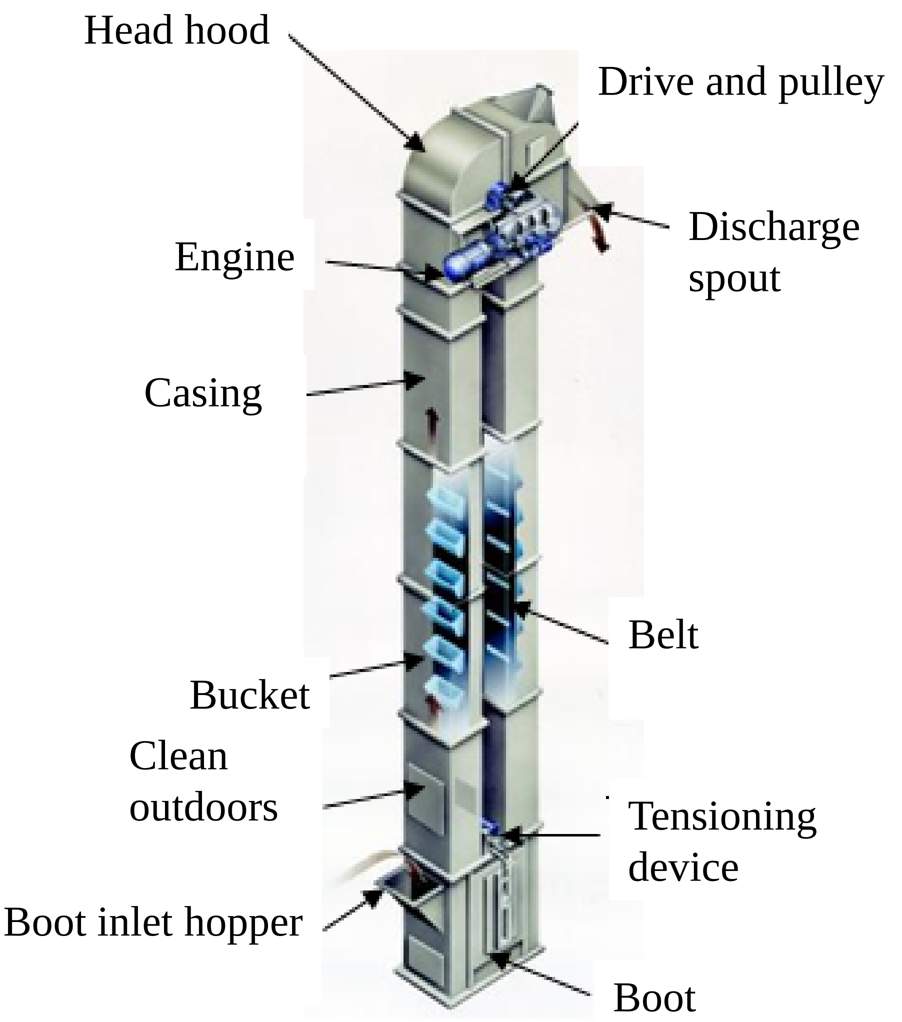


- **Designed with several options to choose height, speed and constructive details depending on the type of material to be transported.**

- **Are constructed by pieces or units to allow definition of the suitable height.**



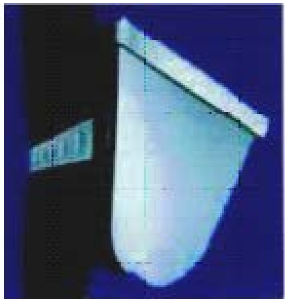
COMPONENTS

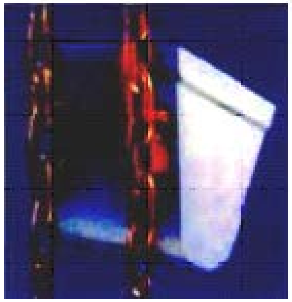

Head hood
Drive and pulley
Discharge spout
Engine
Casing
Belt
Bucket
Clean outdoors
Tensioning device
Boot inlet hopper
Boot

BUCKET ATTACHMENTS

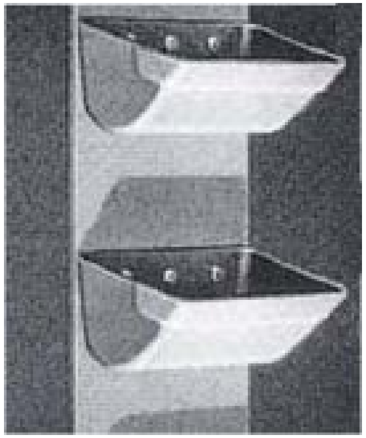
Transmits movement given by the drive pulley

- **Classification:**
  - **Belt**
  - **Chain**





Belt



- **Advantages:**
  - **Less wear.**
  - **Silence operation.**
  - **High specific transport capacity.**
  - **Lower energy consumption.**
  - **The most appropriate to manipulate flour, coal, etc.**
  - **High travelling speeds (up to 2.5 m/s).**

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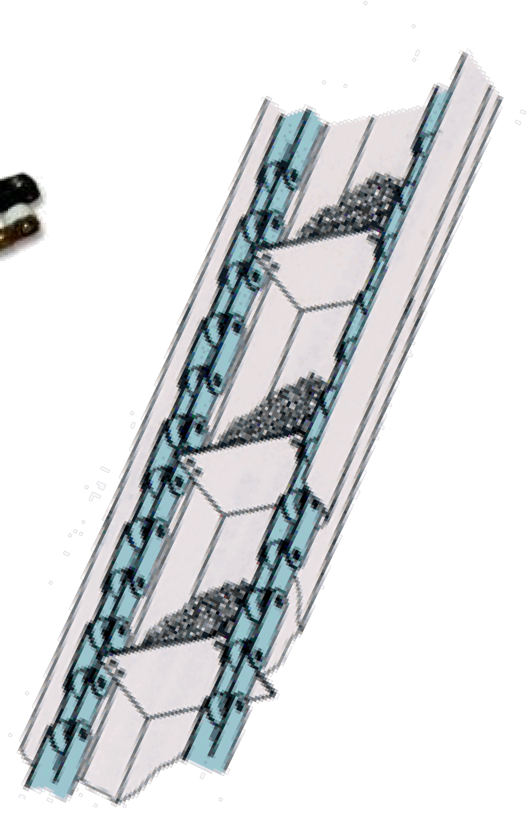
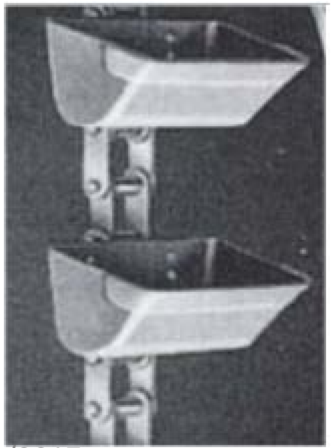
BUCKET ATTACHMENTS

Chain

- **Advantages:**
  - Higher heights
  - Heavier loads
  - Higher temperatures
- **Drawbacks:**
  - Speeds up to 1.25 m/s





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DEPENDING ON THE CONSTRUCTION AND BUCKET PATH

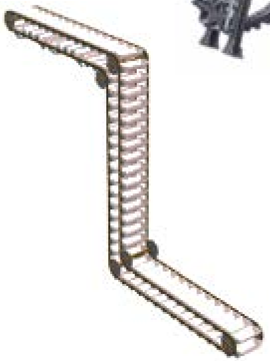
Vertical bucket elevator

- **Designed for vertical or inclined (less than 20º with respect to vertical) material transport.**

Inclined bucket elevator

- **Designed for inclined material transport at 55º to 70º angles with respect to the horizontal.**

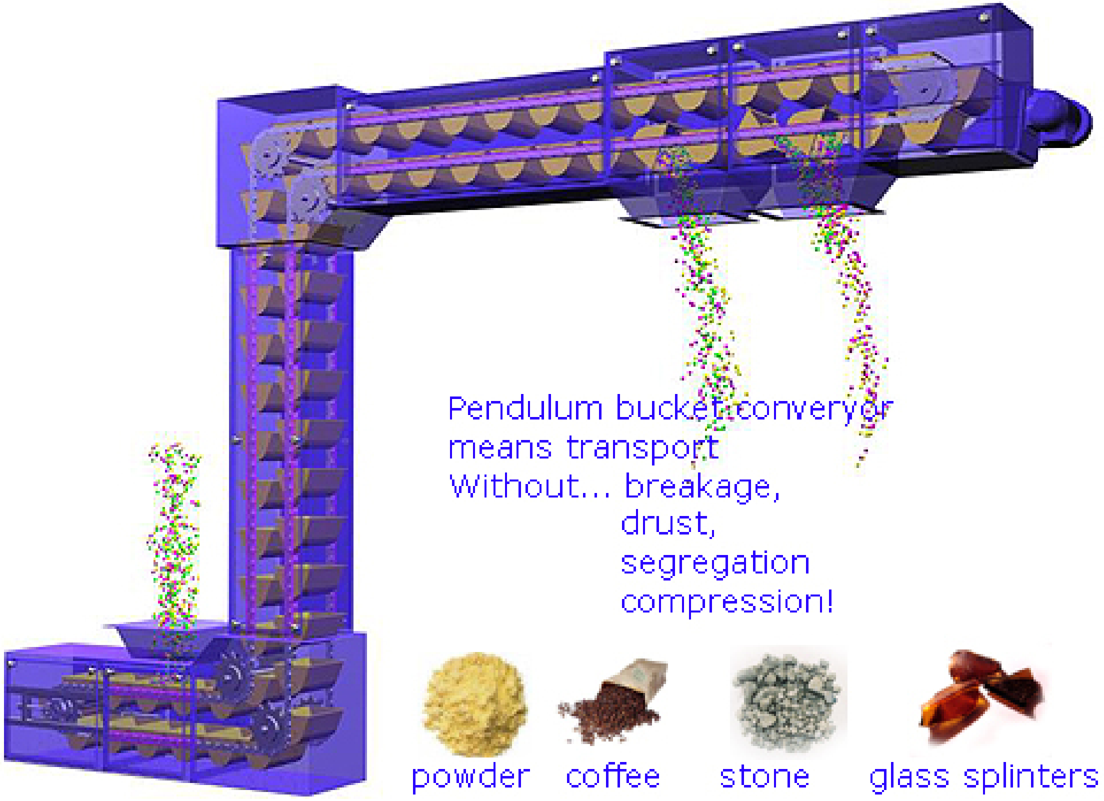
Pendulum bucket conveyor



- **Designed for transport of material between two points located in the same vertical plane at different levels.**

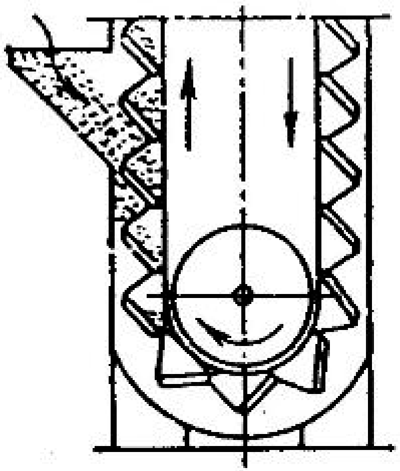
DEPENDING ON THE CONSTRUCTION AND BUCKET PATH

Pendulum bucket conveyor



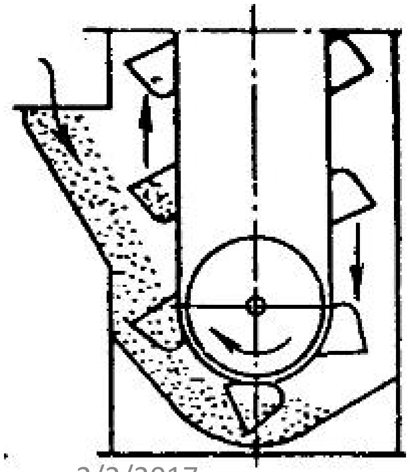
DEPENDING ON THE LOAD

Directly to the input hopper



- Used for transport of abrasive and big size materials.
- Chain/belt travelling speed is low.

By digging



- Used for transport of materials that offer no resistance to extraction, like fine grain and dusty materials.

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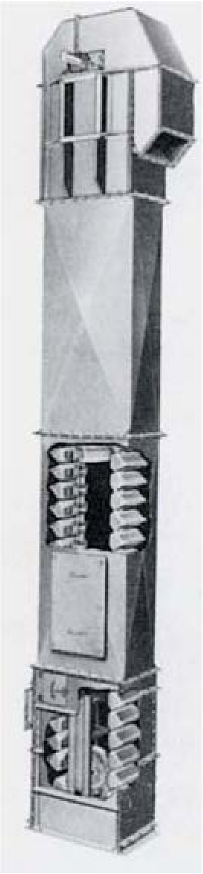
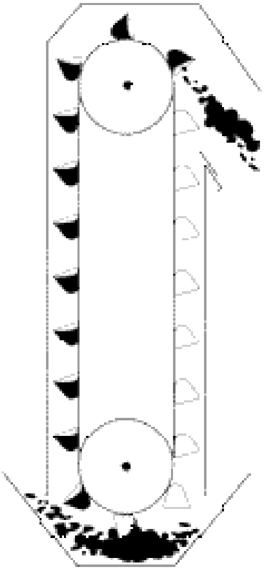
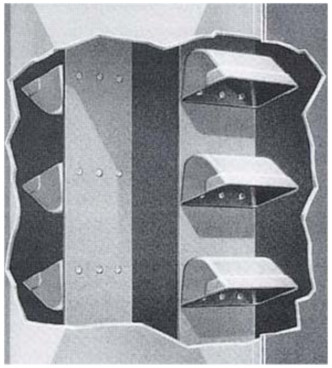
DEPENDING ON THE TYPE OF DISCHARGE

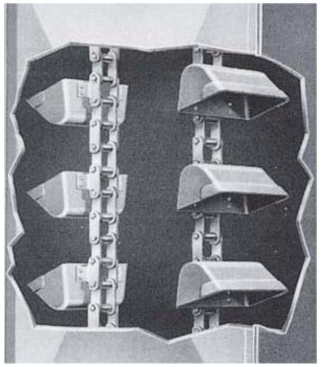


Centrifugal

- It is the most common.
- Great travelling speeds (1.2 and 1.4 m/s).
- Loading is carried out by dredging the material at the bottom of the elevator.
- The separation distance between the buckets is 2 to 3 times the bucket height.







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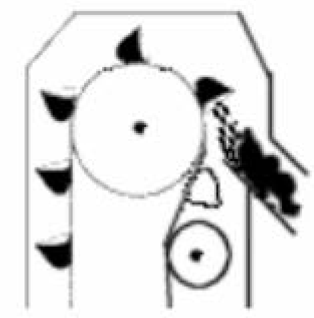
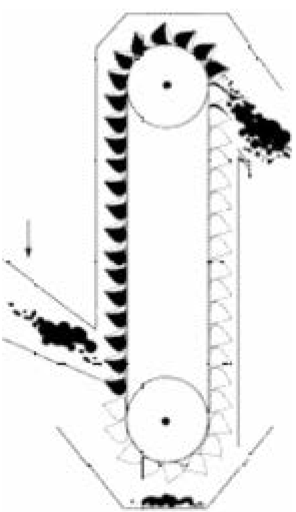
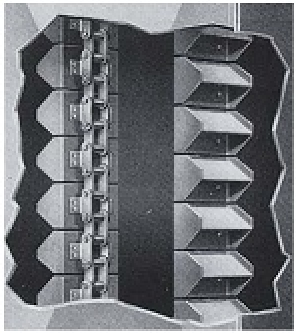
DEPENDING ON THE TYPE OF DISCHARGE

Gravity or continuous

- **Lower travelling speeds (0.5 and 1.0 m/s).**
- **It is taken advantage of self weight.**
- **Classification:**
  - **Free gravity.** It is necessary to change the free branch line or incline the bucket.
  - **Forced.** The buckets are situated one after the other without separation between them. The discharge takes place due to gravity by means of the lower part of the preceding bucket that acts as a discharge spout.







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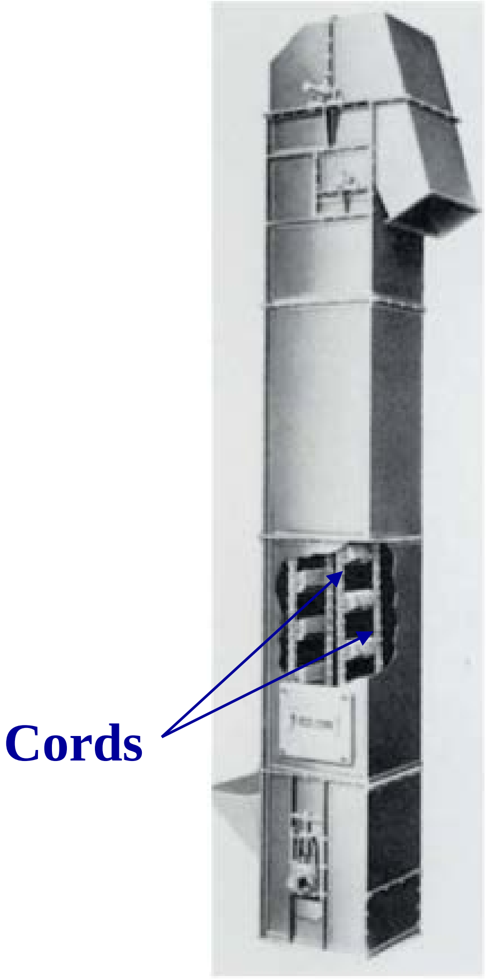
DEPENDING ON THE TYPE OF DISCHARGE

Positive

- **Similar to the gravity elevator except that buckets are fitted at the edges with two cords.**
- **Bucket speed is low, which is appropriate for light, aired, sticky materials.**



Space Mining Equipment Prototypes

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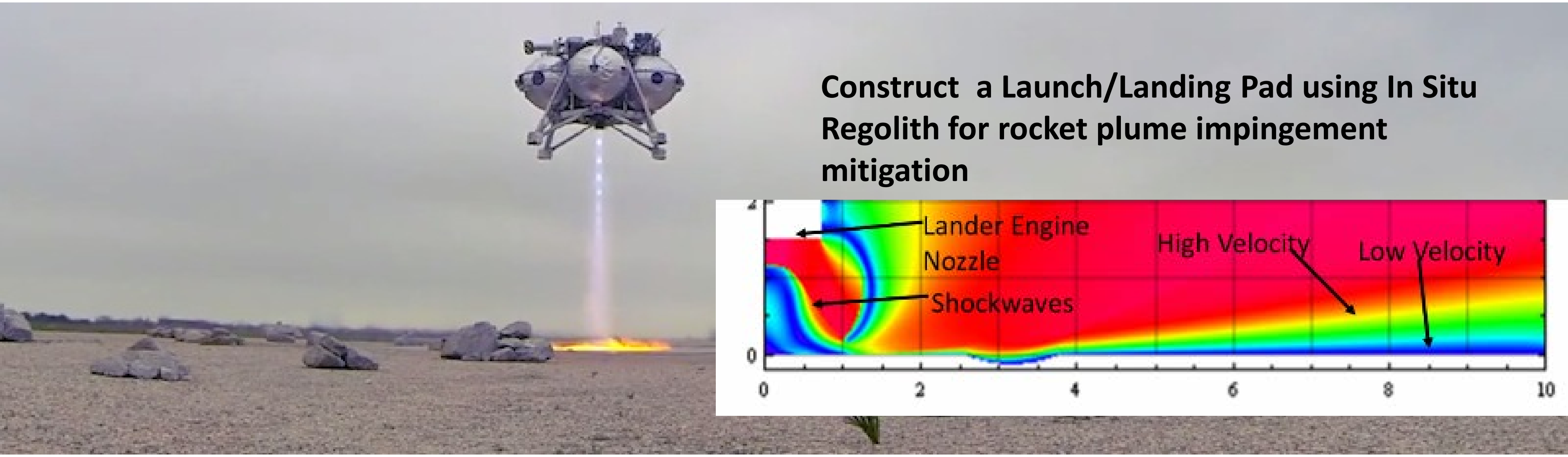
Launch / Landing Pad Construction

Construct a Launch/Landing Pad using In Situ Regolith for rocket plume impingement mitigation



NASA Chariot Bull Dozer

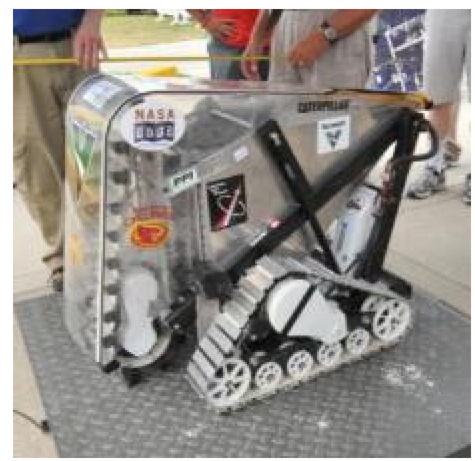
Hawaii PISCES Rover on Mauna Kea with Payloads

What is the Best Lunabot Regolith Mining Design for the Moon?? The Most Popular Winning Design? (50-80 Kg)

2009: Paul's Robotics WPI

2010: Montana State U

2011: Laurentian University



2012: Iowa State U

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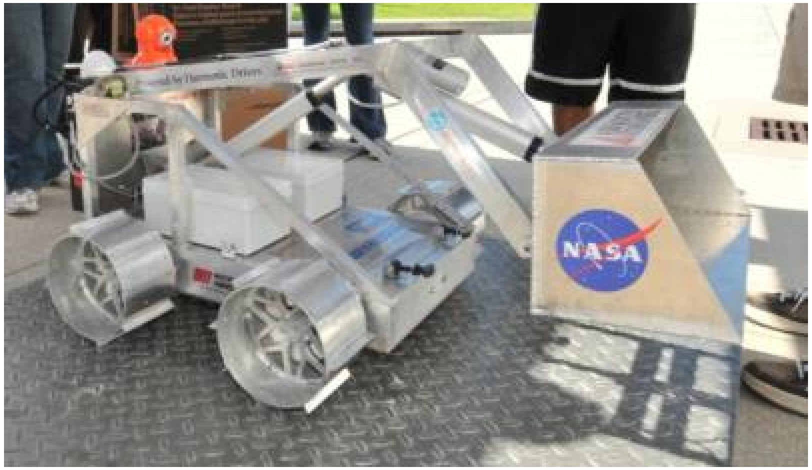
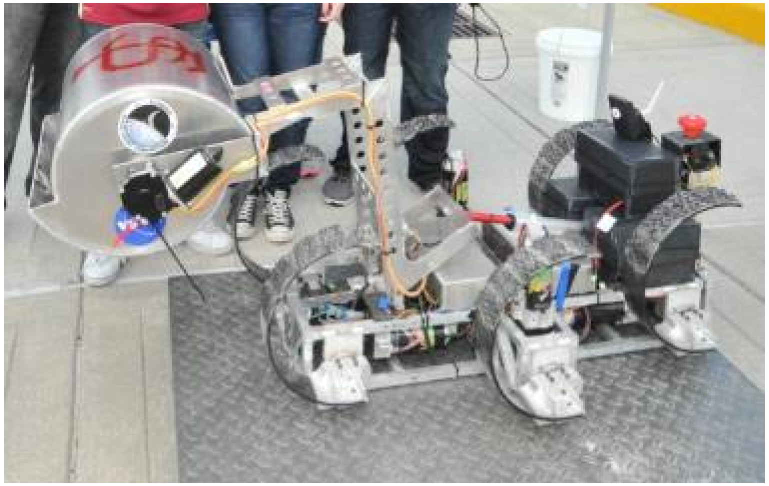
Or are these designs better?



2012: Embry Riddle Daytona AU

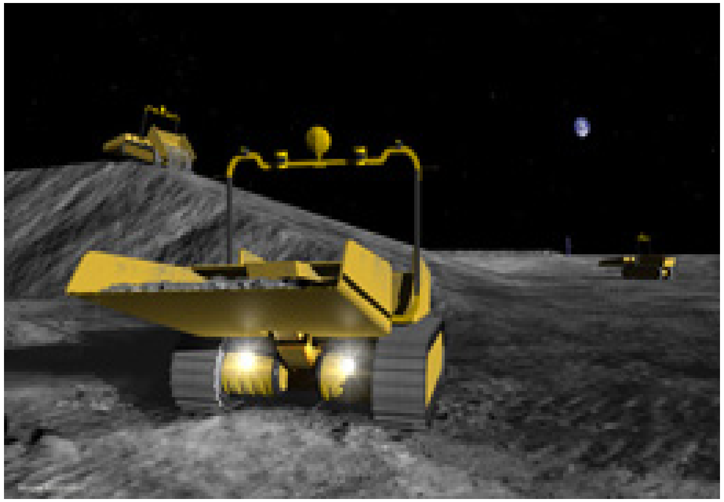
2011: U North Dakota



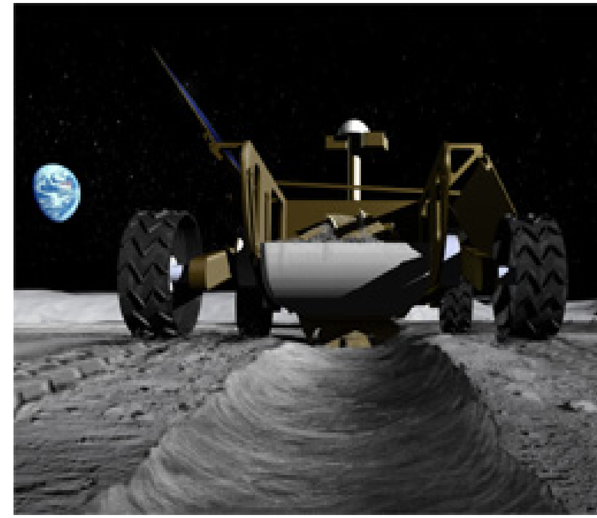
2012: FAMU/ Florida State U

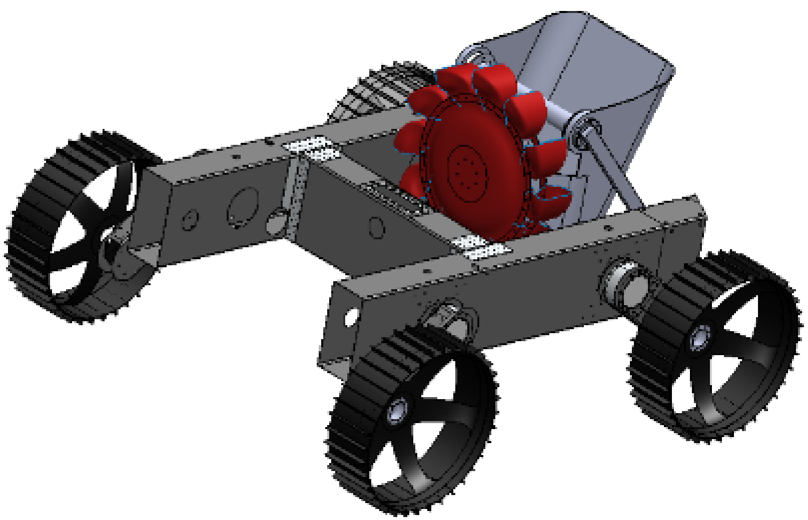
2012: Montana State U

Astrobotic Technology inc. Lunar Mining Concepts NASA SBIR 2010-2012



ASTROBOTIC





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NASA KSC Swamp Works
Regolith Advanced Surface Systems Operations Robot (RASSOR)


RASSOR 1.0 Prototype


RASSOR 1.5 Prototype

RASSOR 2.0 Prototype
Dry Mass = 50 Kg
Regolith Payload = 80 Kg
Counter-Rotating Bucket Drums = Zero Net Reaction Force

Construction Equipment

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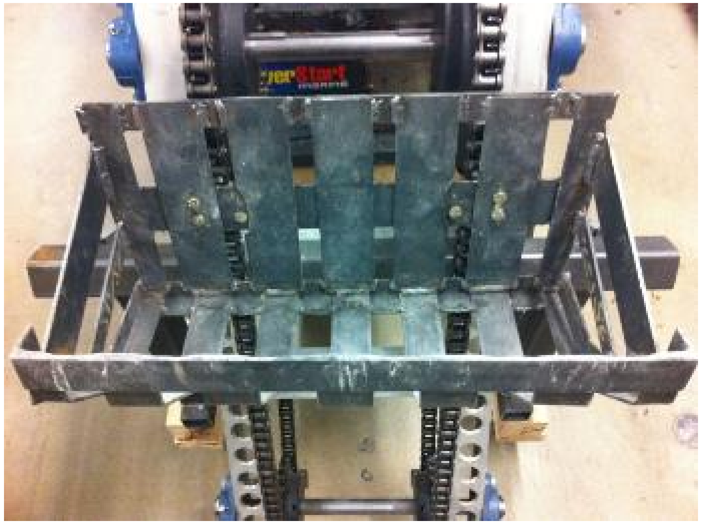
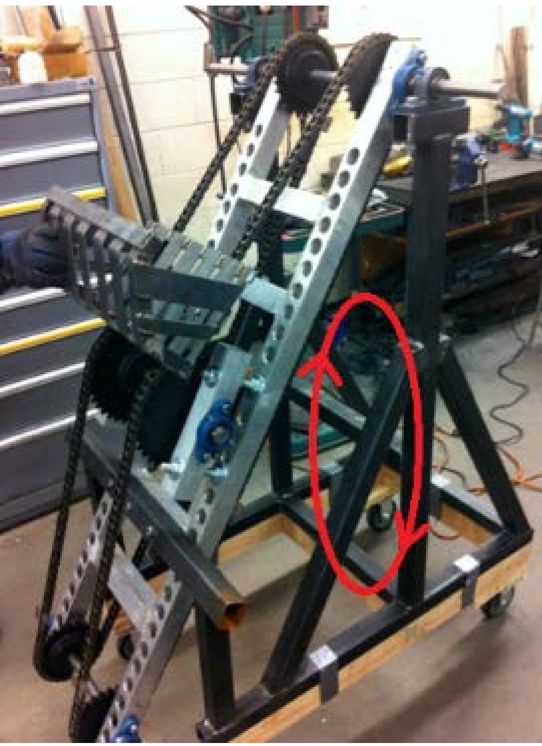
Prototype Testing

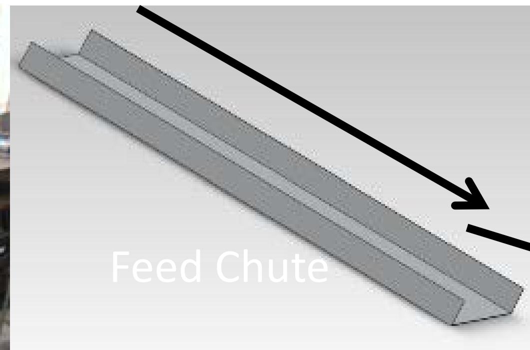
- Simulated Moon Rocks
- Sorting 99% efficient

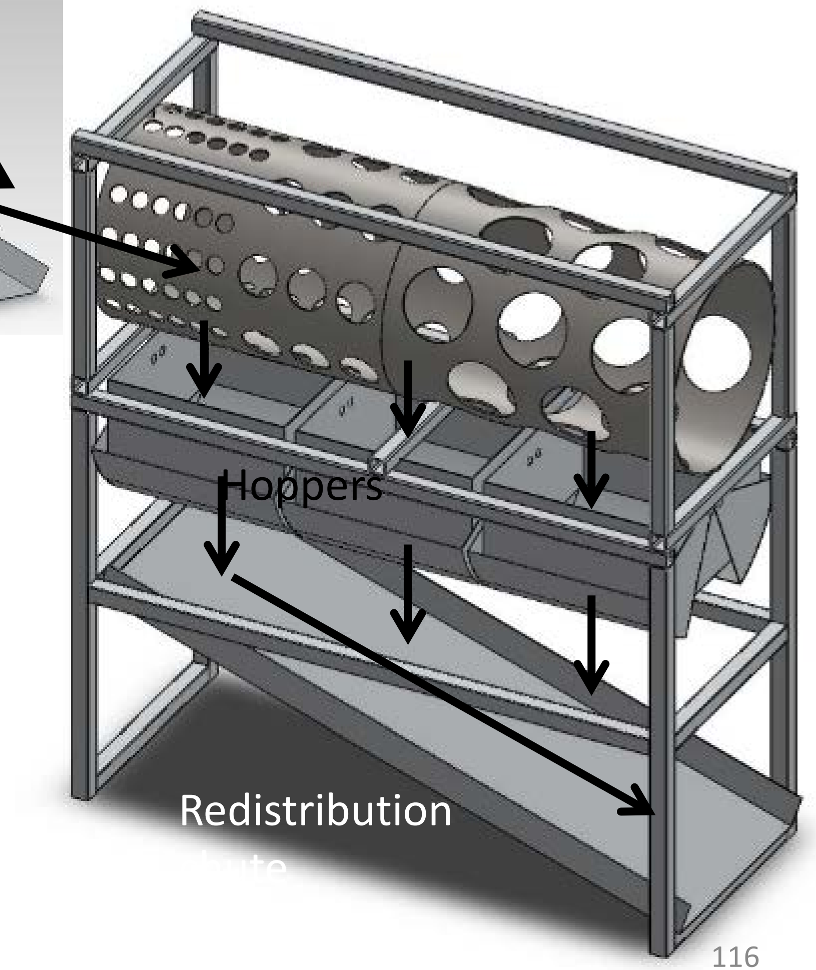


Rock Path through tool



Bucket Ladder





Ore Temperature Processing Choice

- Water available from various feedstocks is a function of the temperature at which ore is processed.
- For hypothesized deposits, processing temperatures would be selected where "most" of water is extracted at lowest reasonable temperature / power points.
- For typical martian regolith, two scenarios considered, based on two dominant mineral phases (see following).
  - Hypothesis: Lower temperature processing may require more feedstock, but might result in less power required.
  - [Note: Upon analysis, this hypothesis was subsequently proven false – processing greater mass of ore in same amount of time resulted in roughly equivalent power required.]
  - Additionally, regolith processing temperatures above 450 C may release corrosive contaminants which may be harmful to equipment for diminishing returns of water.

Energy Calculation Method

- Feedstock definition (specifically, water availability per processing temperature) used to determined mass of each type of ore needed to achieve water production target.
  - Assumed 75% efficiency of water removal from ore.
- Calculated heat necessary to raise ore temperature to dehydration temperature and added heat of dehydration.

$$\Delta H = m\ c_p\ \Delta T + \Delta H_{dehydration}$$

  - Current analysis assumes heat loss to calcination reactor is negligible compared to heat required to raise ore temperature (i.e. thin walled, well-insulated) [Assumption may need to be revisited in future work].
- Power Required = ΔH / time
  - Calculated for both continuous processing and “batch-mode” –essentially same power required with either calculation.
  - Batch mode assumed two hours to heat up each batch of ore.