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Adaptation of Mining Methods for Low- and Micro-gravity Environments: Part 1

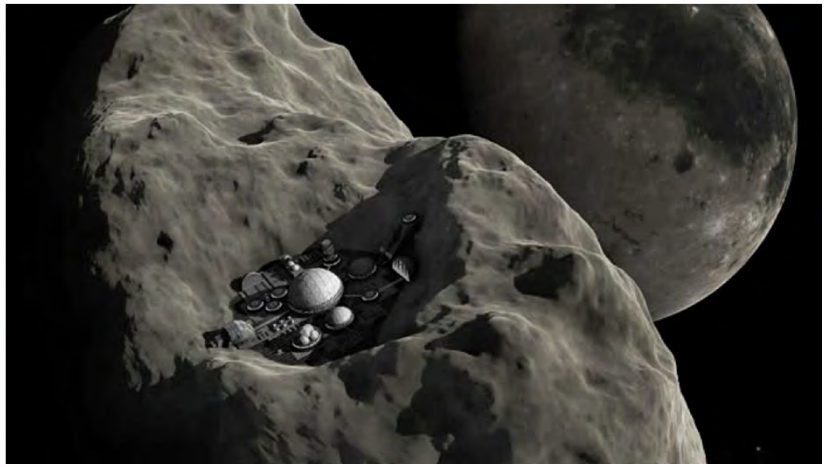
Outline

First progress report …

- Introduction
  - Non-terrestrial mining
  - Near-term targets
  - Stages of mining
- Study procedure
  - Capabilities needed for non-terrestrial mining
  - Mining methods
  - Mining unit operations
  - Typical surface mine operations sequence
- Results to date
  - General effects of gravity
  - On fragmentation
  - On excavation
  - On transport
- Conclusions / Recommendations

Non-terrestrial Mining

- Definition:
- Extraction of natural resources outside Earth
  - space mining, lunar mining, asteroid mining
  - is the first capability required for *in situ* resource utilization (ISRU)



- Purpose:
- Support Earth economy
  - ensure supply of critical minerals
  - create new materials
- Protect Earth by providing
  - material for creation & maintenance of infrastructure in space
  - mitigation of population increase and life demands
  - capability to disassemble potential impactors
- Support exploration of space
  - reduce launch mass
  - go farther

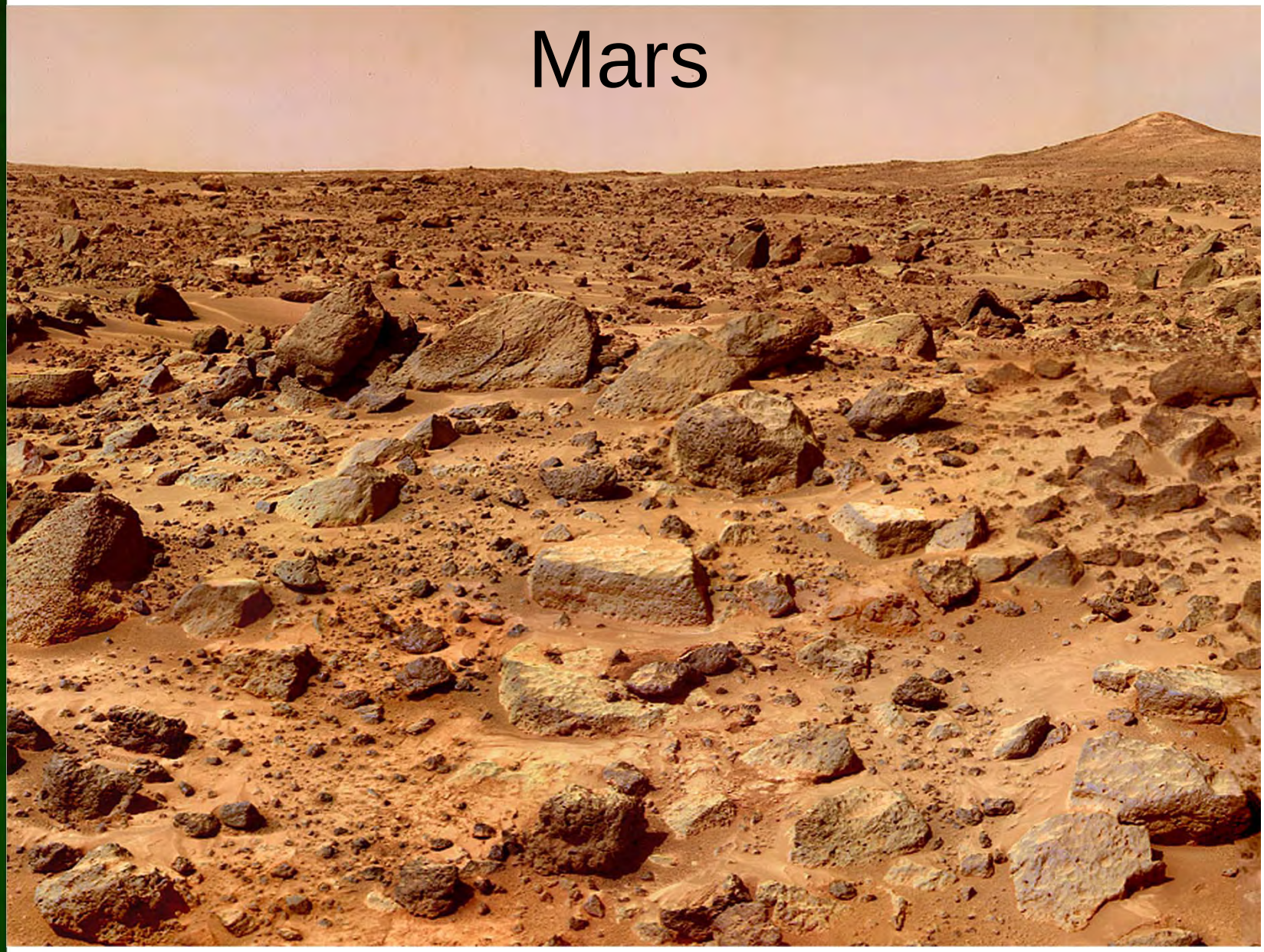
image from Anderson (2012)

Earth's Moon

Apollo 16

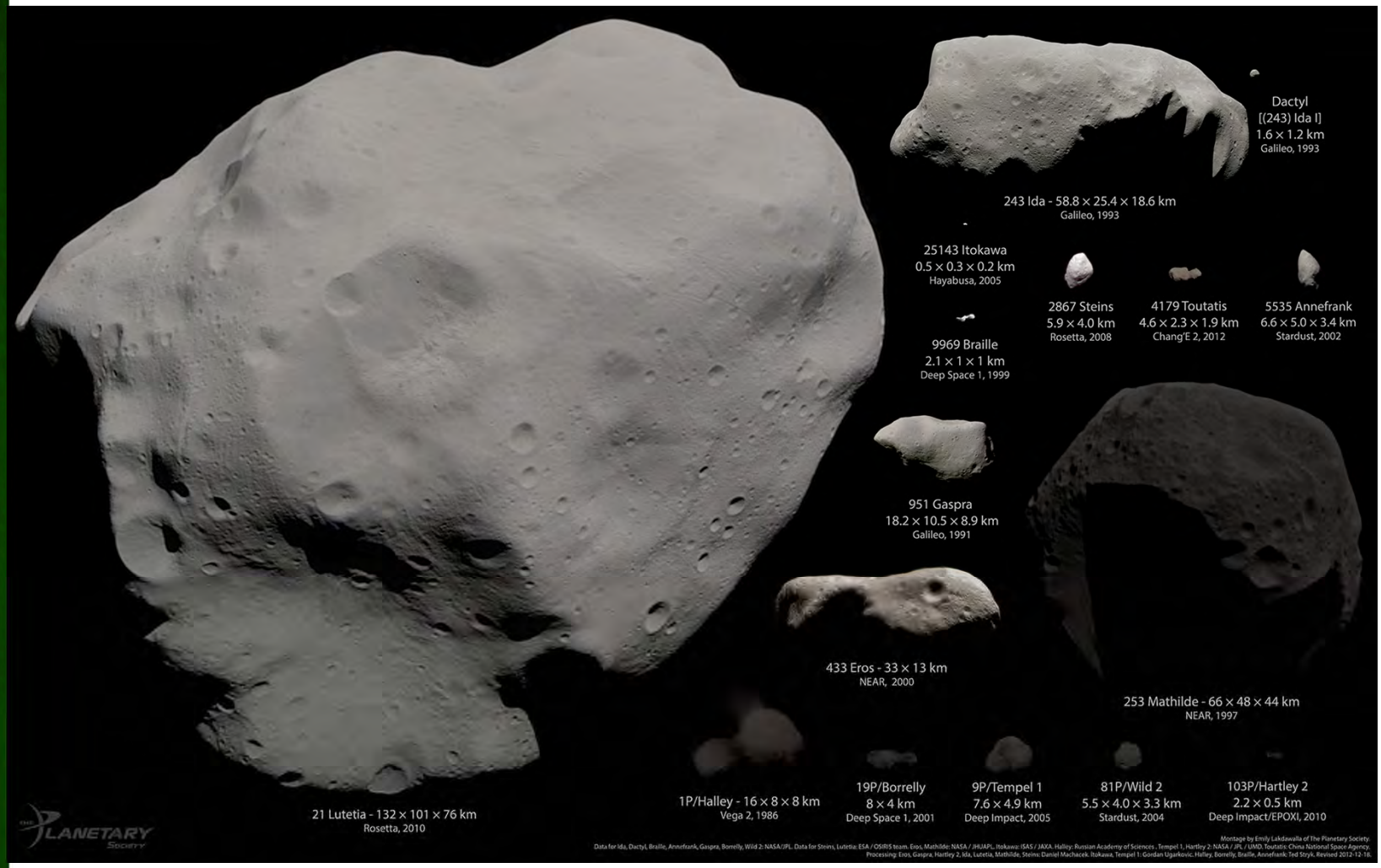
NASA

Mars



http://snowbrains.com/brain-post-how-the-nasas-curiosity-has-proven-that-mars-once-had-an-atmosphere/

Asteroids



Montage by Emily Lakdawalla (2013). Data from NASA / JPL / JHUAPL / UMD / JAXA / ESA / OSIRIS team / Russian Academy of Sciences / China National Space Agency.

Stages in the Life of a Mine

- prospecting
  - search for potentially valuable mineral deposits
- exploration
  - determines the size and value of promising mineral deposits
- development
  - opening up and maintaining access to the orebody
- production
  - the actual recovery of the target minerals
- reclamation
  - closing the mine and restoring the land to ensure safety and future utility

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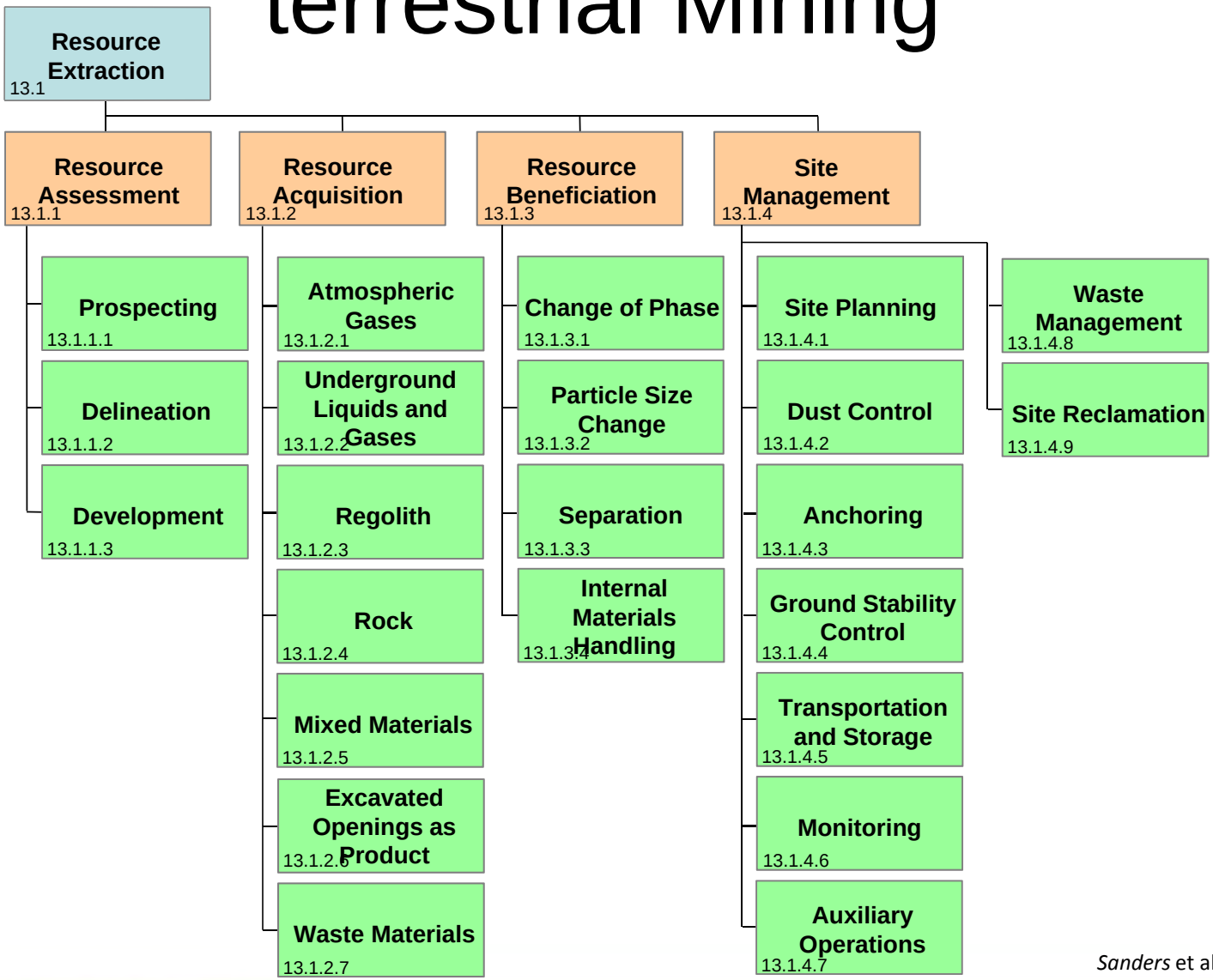
Capabilities Needed for Non-terrestrial Mining



Sanders et al. *(2005)*

Major Mining Methods

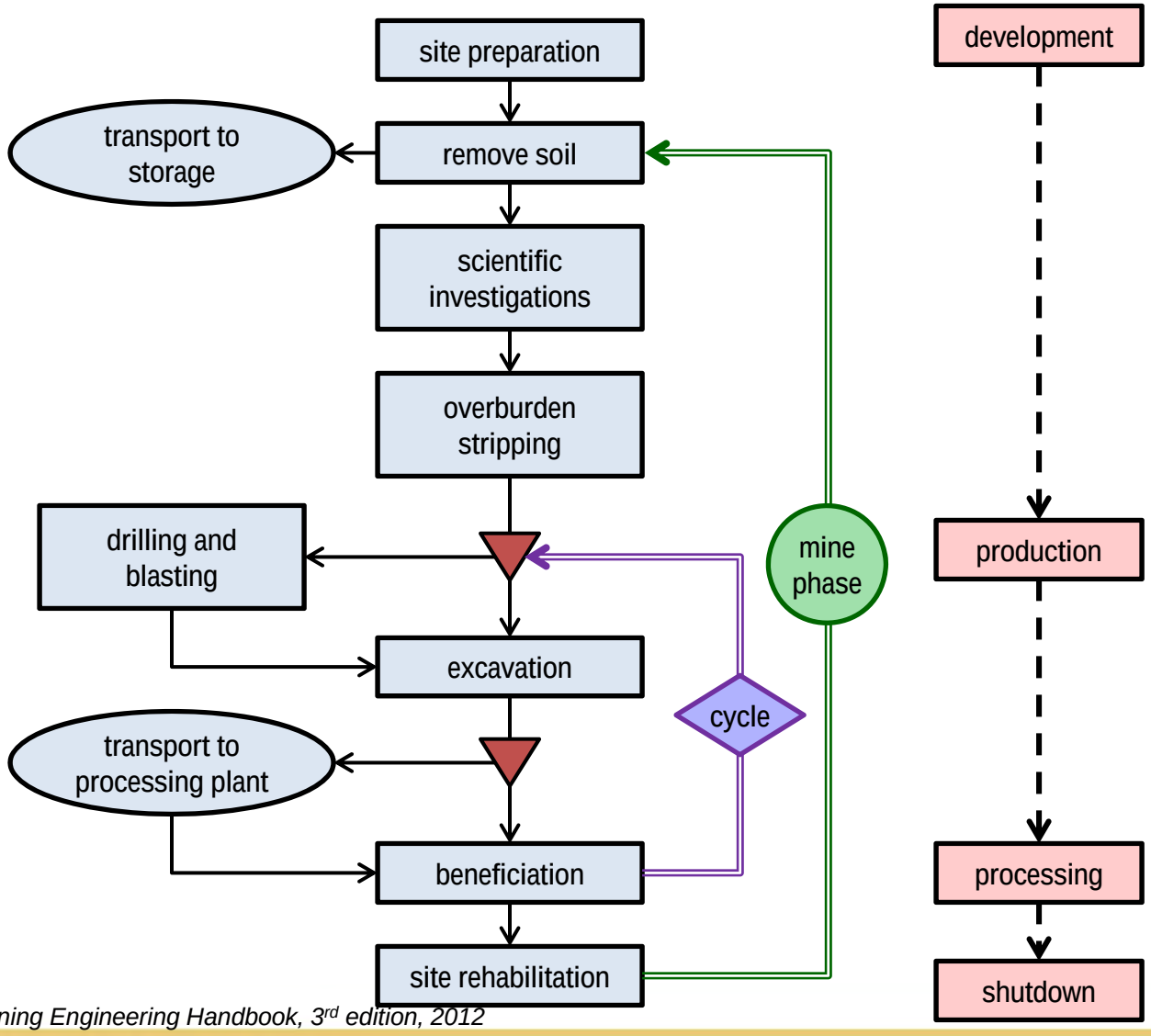
Access	Class	Method	Terrestrial Commodities Mined	Relative Cost
Surface	Mechanical	Open Pit	metal, nonmetal	5%
		Quarrying	nonmetal	100%
		Open-Cast	coal, nonmetal	10%
		Augering	coal	5%
	Aqueous	Hydraulicking	metal, nonmetal	5%
		Dredging	metal, nonmetal	<5%
		Borehole Mining	nonmetal	5%
		Leaching	metal	10%
Underground	Self-Supported	Room-and-Pillar	coal, nonmetal	20%
		Stope-and-Pillar	metal, nonmetal	10%
		Shrinkage Stoping	metal, nonmetal	45%
		Sublevel Stoping	metal, nonmetal	20%
	Artificially Supported	Cut-and-Fill	metal	55%
		Stull Stoping	metal	70%
		Square-Set Stoping	metal	100%
	Caving	Longwall/Shortwall	coal, nonmetal	15%
		Sublevel Caving	metal	15%
		Block/Panel Caving	metal	10%

Hartmann and Mutmansky (2002)

Unit Operations of Mining

- production operations – obtain the ore
  - fragmentation – breaks rock away from its surroundings
  - excavation – picks it up
  - transportation – hauls it
  - beneficiation – prepares it for processing
- processing operations – separate ore from waste
  - comminution (crushing and grinding)
  - separation
  - transportation

Typical Terrestrial Surface Mine Operations Sequence



after SME Mining Engineering Handbook, 3rd edition, 2012

Effects of Gravity

- Direct effects
  - excavation forces
    - drilling weight-on-bit
    - excavator bite
    - bucket fill
  - blast casting
    - combined fragmentation, excavation, & transportation
  - materials transport
    - conveyor capacities
    - sparse-gas slurries for pipe flow
  - general transportation
    - ground contact parameters
    - slopes
- Indirect effects
  - modified terrestrial mining methods
    - relative contributions of gravity-affected parts of unit operations
    - aggregate time/energy distributions different than on Earth
  - new mining methods

Excavation Force Requirements

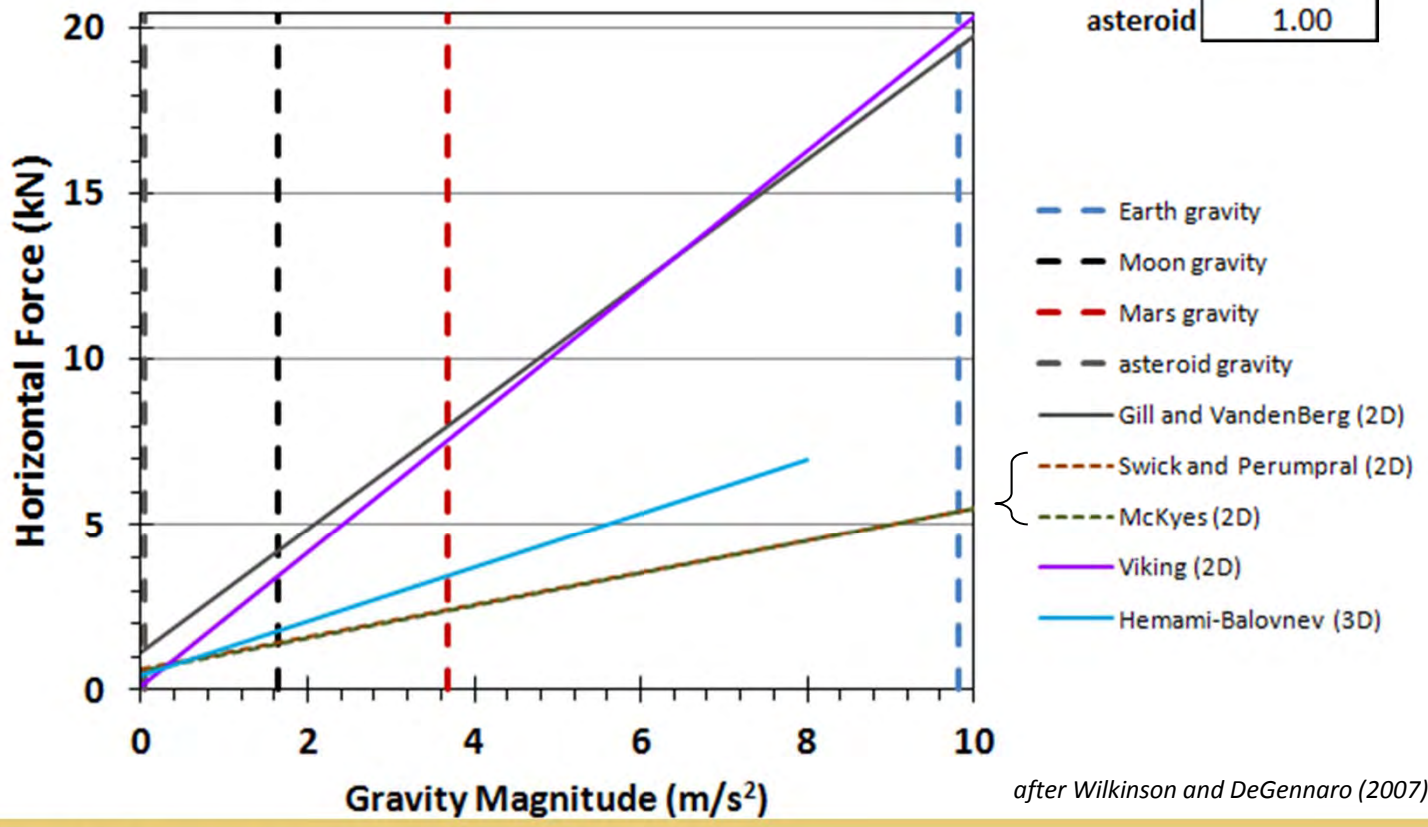
- Mechanical Excavation
  - vertical (sumping, normal) force
    - supplied by machine weight
  - horizontal (shearing, tangential) force
    - supplied by machine traction
  - fragmentation (*e.g.* ripping) can be separate operation from excavation
    - excavator digs loose material (vs. bank material)
- Drilling and Blasting
  - drilling
    - vertical force (thrust, weight-on-bit) – supplied by drill weight
    - horizontal (tangential) force – supplied by drill torque
  - blasting
    - heave – horizontal distance moved
    - throw – vertical distance moved
  - excavation
    - blast-casting
    - excavation machines

Horizontal Excavation Force

- Required for:
  - blading/scraping/slushing
  - excavator bucket fill

- Prediction ranges:

Δ Horiz Force (kN)	
Earth	14.58
Moon	2.80
Mars	5.61
asteroid	1.00

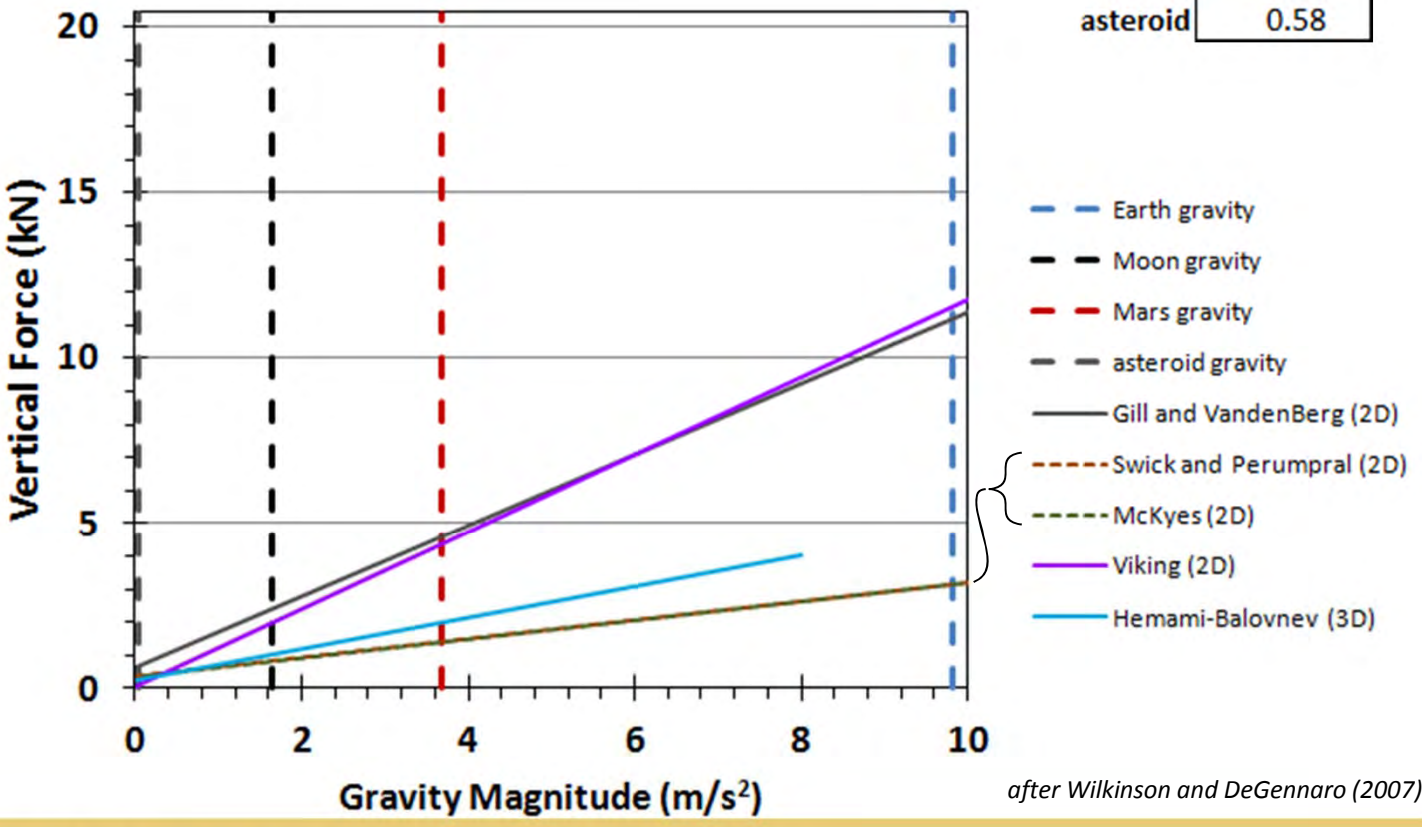


after Wilkinson and DeGennaro (2007)

Vertical Excavation Force

- Assumptions:
  - lunar regolith properties (Heiken *et al*. 1992)
  - rake angle = 45°, force resultant angle = 15 °
- Prediction ranges:

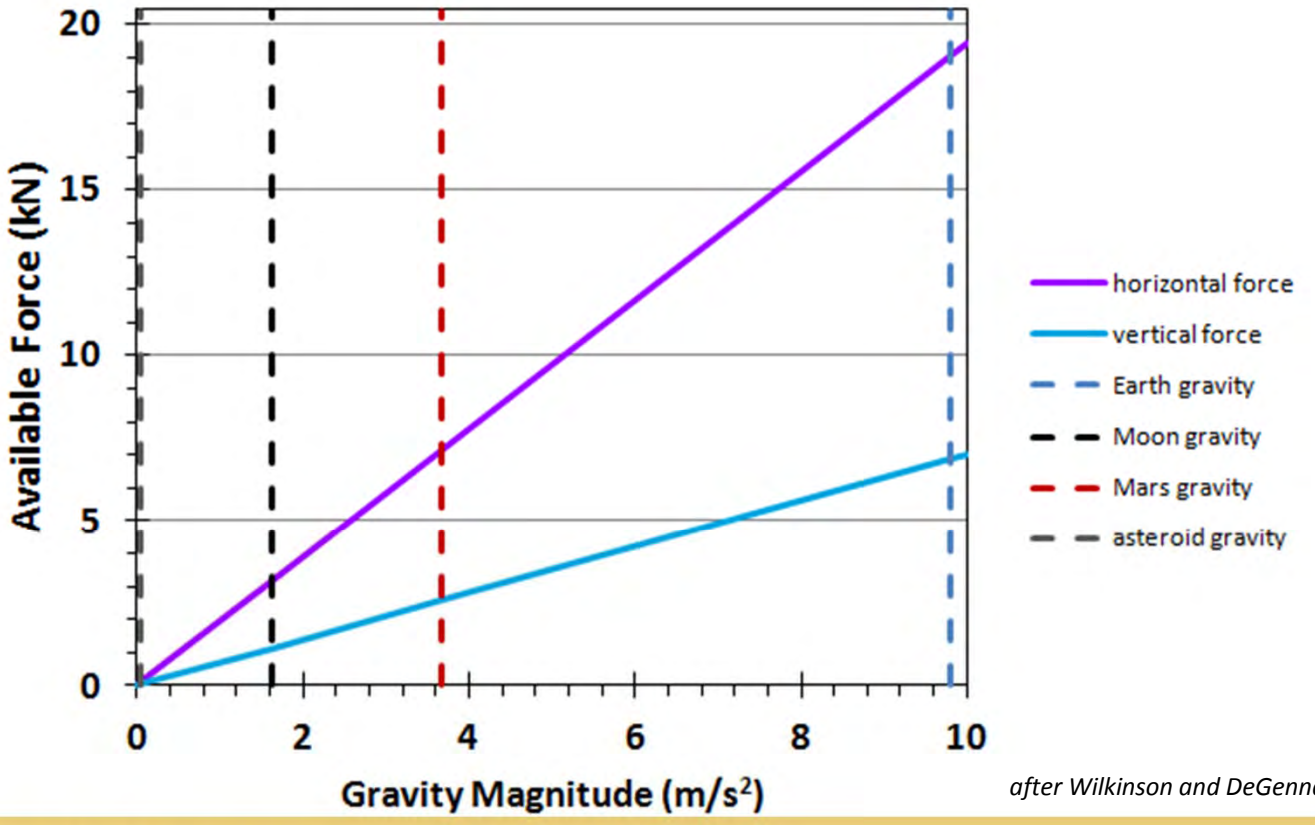
	Δ Vert Force (kN)
Earth	8.42
Moon	1.62
Mars	3.24
asteroid	0.58



after Wilkinson and DeGennaro (2007)

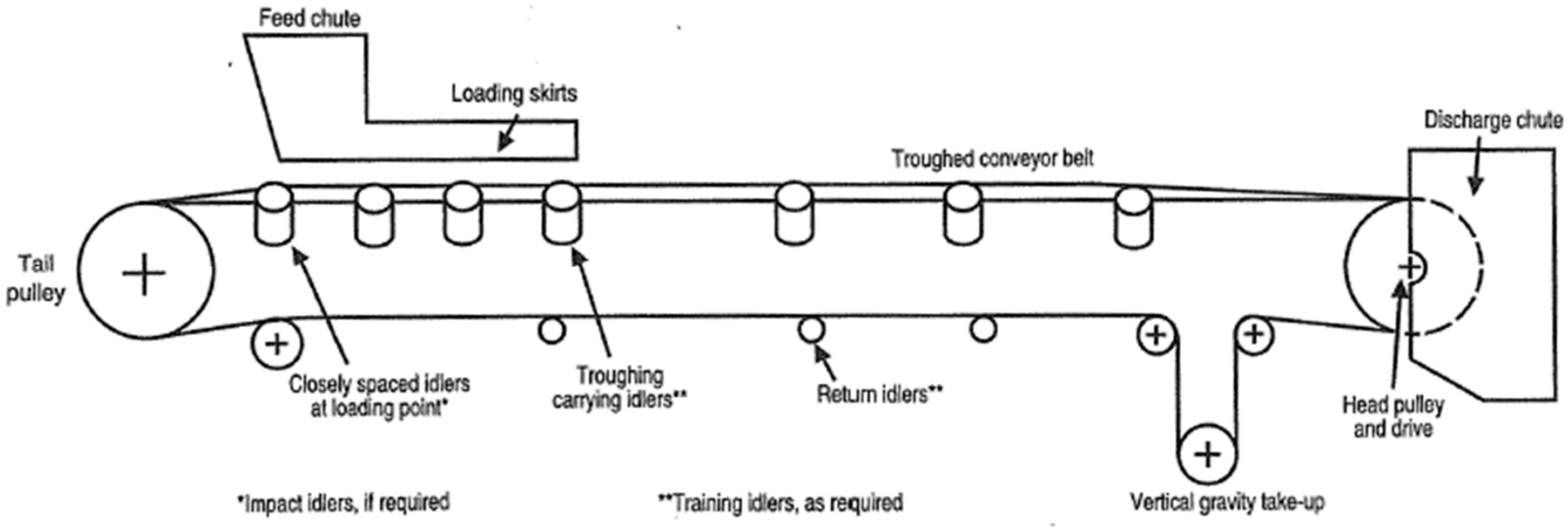
Available Force

- Assumptions:
  - ground pressure 5 kPa
  - machine mass 700 kg



after Wilkinson and DeGennaro (2007)

Material Handling: Conveyors



Conveyor Equipment Manufacturer's Association (1997)

Material Handling: Conveyors

- Belt tension and power requirements
  - transported material
    - surcharge angle may be greater than on Earth
  - belt materials
    - different densities
    - different tensile and shear strengths, different moduli (sag)
  - pulleys and idlers
    - bearings will have different rotating resistance
    - covers will have different friction coefficients
- Transfer points
  - troughing
  - chutes
  - load centering
  - skirtboards

Material Handling: Conveyors

Flow				
Very free flowing 1*	Free flowing 2*	Average flowing 3*		Sluggish 4*
Angle of Surcharge				
5°	10°	20°	25°	30°
				
Angle of Repose				
0-19°	20-25°	30-34°	35-39°	40° - up
Material Characteristics				
Uniform size, very small rounded particles, either very wet or very dry, such as dry silica sand, cement, wet concrete, etc.	*Rounded, dry polished particles, of medium weight, such as whole grain and beans.*	*Irregular, granular or lumpy materials of medium weight, such as anthracite coal, cottonseed meal, clay, etc.*	*Typical common materials such as bituminous coal, stone, most ores, etc.*	*Irregular, stringy, fibrous, interlocking material, such as wood chips, bagasse, tempered foundry sand, etc.*

Conveyor Equipment Manufacturer's Association (1997)

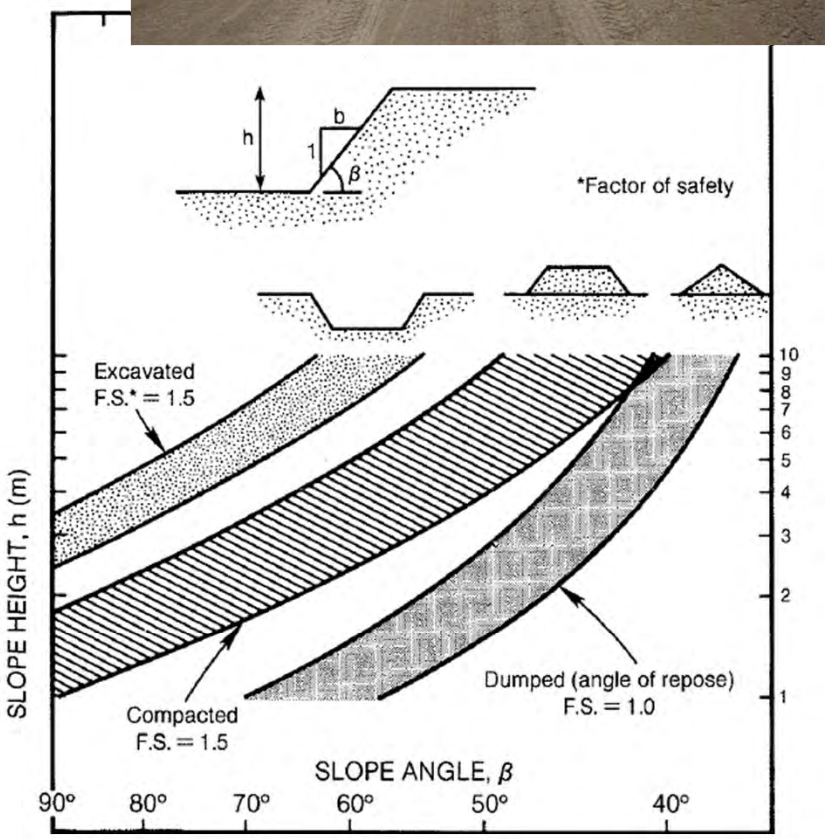
Material Storage

- Material bulking (bank → loose) may vary inversely with gravity magnitude
  - terrestrial values 20%-50%, seldom less than 5%
  - likely to be three values:
    - undisturbed
    - artificially compacted
    - loose
- Cohesive effects of atmospheric moisture absent
  - does cohesion increase without meteroid impact vibrations?

General Transportation

Kansas road in loess has eroded 4.6 m in ~60 years.

- Trafficability and slopes
  - before disturbance (natural)
    - cohesion is non-zero
    - friction angle same as Earth
    - angle of repose slightly higher than friction angle
  - artificially compacted
    - intermediate cohesion
    - friction angle same as Earth
    - angle of repose less than friction angle
  - loose (stockpile)
    - cohesion zero
    - angles same as artificial case



Calculated stability of three types of slopes in lunar regolith (Lunar Sourcebook, 1991).

Expectations

- No true conclusions reached yet.
- Direct gravity effects on unit operations:
  - fragmentation and excavation effectiveness may lie in less brute force, more finesse and smarts
  - robustness, flexibility, and ease of maintenance or cheapness may lead to surprising combinations of high- and low-tech approaches
- Indirect gravity effects on unit operations:
  - engineered systems effects, may be non-intuitive
- Effects of gravity combinations with other environmental parameters:
  - also may be non-intuitive

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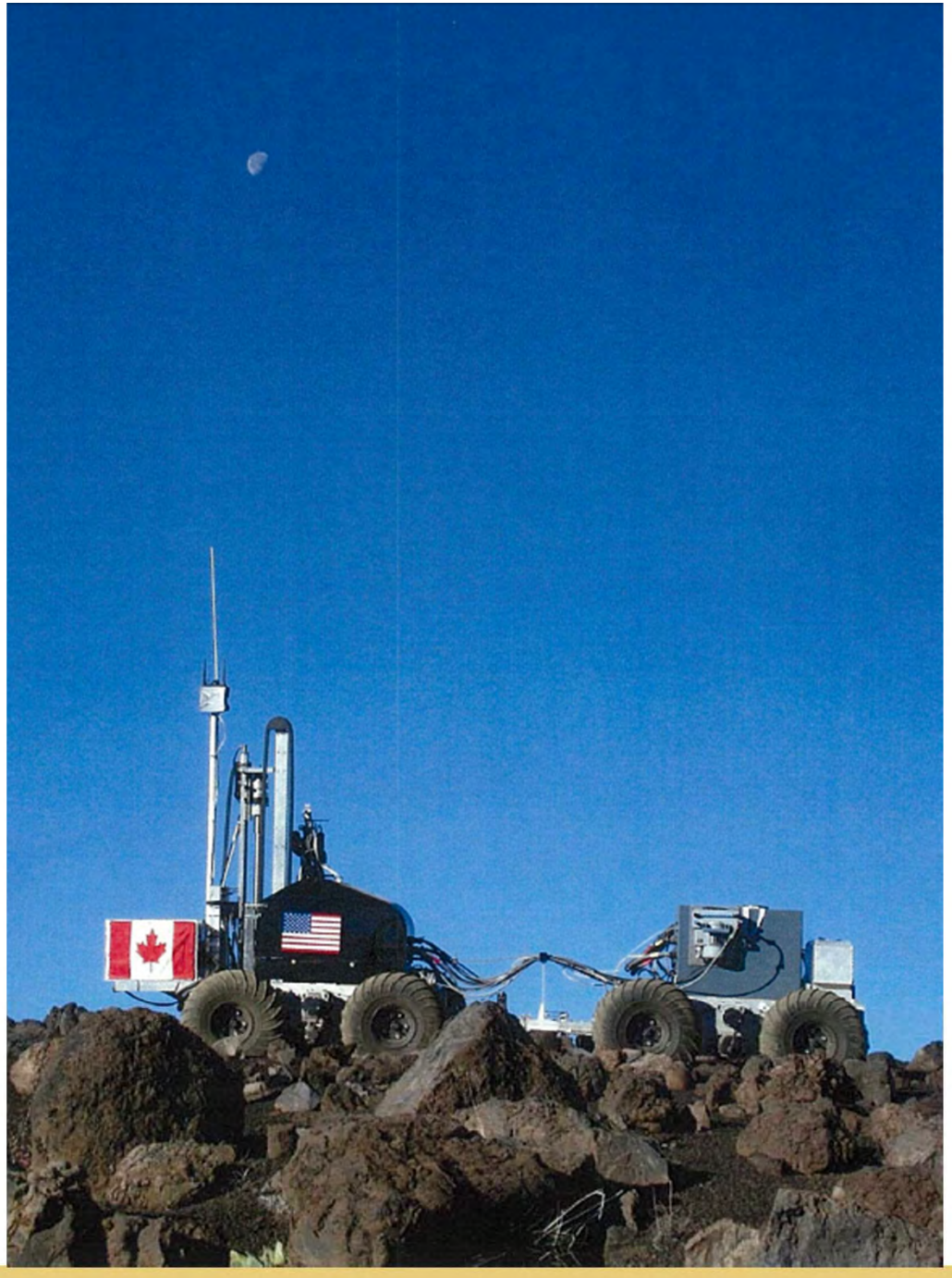
Future and Parallel Work

- Future work planned:
  - finish breaking down unit operations
  - complete identification of gravity effects on unit operations technologies
  - evaluate indirect gravity effects on major mining methods
  - reconstruct modified terrestrial mining methods
  - create new mining methods
  - simulate most promising non-terrestrial mining methods
- Parallel work needed:
  - catalog secondary and tertiary effects from modifications in materials and design-for-task for lunar, martian, and asteroidal environments



Effects Other Than Gravity

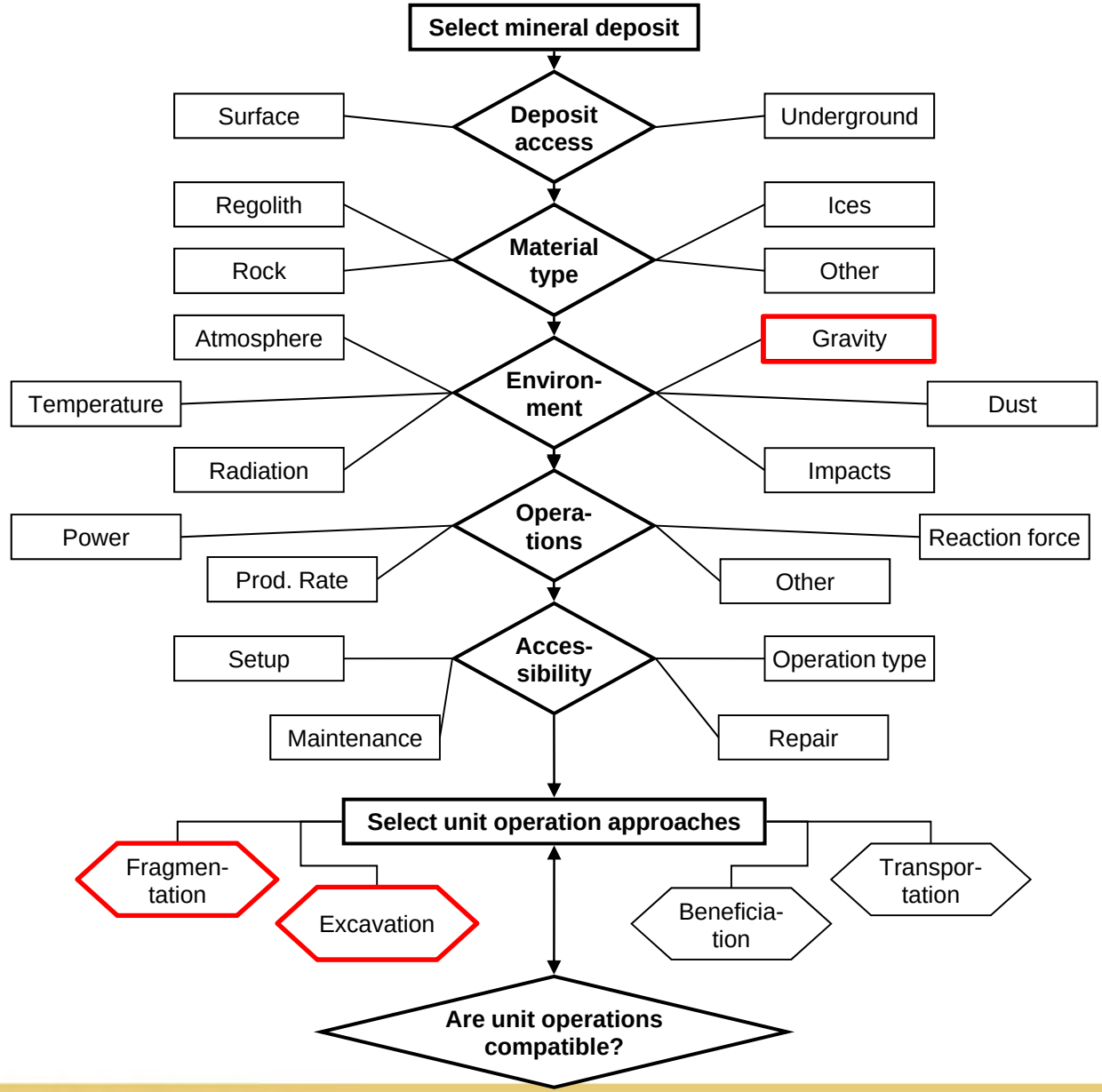
- Atmosphere
  - thin or absent
  - heat dissipation more difficult
- Topography
  - controlled by impacts
    - body history
    - craters
    - regolith depth
  - affects shadows and thus temperature
  - surface roughness
- High-energy radiation
  - many types
  - some continuous (chronic)
  - some acute
- Power availability
- Unfamiliar diurnal cycle

Non-Terrestrial Environments

	Earth's Moon	*Mars*	*asteroids*	*comets*	*gas giants*	*ice giants*	*remote icy bodies*
Environment Parameters	Abrasive dust	Dust	Micro-gravity	Micro-gravity	High gravity	High gravity	Reduced gravity
	Low gravity	Low gravity	Variable gravity vector	Variable gravity vector	No solid surfaces	High winds	Possibility of life
	Hard vacuum	Low atmos. pressure	Hard vacuum	Hard vacuum	Corrosive gases		
	High radiation	CO_2 atmosphere	High radiation	High radiation			
	Meteoroid impacts	Low insolation	Very low insolation	Very low insolation	Ultra-low insolation	Ultra-low insolation	Ultra-low insolation
	Extreme temperatures & steep temp gradients	Moderately extreme temperatures	Extreme temperatures & steep temp gradients	Extreme temperatures & steep temp gradients	Extreme temps and pressures	Extreme temperatures	Extreme temperatures
Operational Limits	Power	Power	Power	Power	Power	Power	Power
	Prod. rate	Prod. rate	Prod. rate	Prod. rate	Prod. rate	Prod. rate	Prod. rate
	Humans not avail. for physical labor	Humans not avail. for physical labor	Humans not avail. for physical labor	Humans not avail. for physical labor	Humans not avail. for physical labor	Humans not avail. for physical labor	Humans not avail. for physical labor
Accessibility Limits	Setup	Setup	Setup	Setup	Setup	Setup	Setup
	Operation	Operation	Operation	Operation	Operation	Operation	Operation
	Repair & maintenance	Repair & maintenance	Repair & maintenance	Repair & maintenance	Repair & maintenance	Repair & maint.	Repair & maintenance
Launch Limits	Mass	Mass	Mass	Mass	Mass	Mass	Mass
	Volume	Volume	Volume	Volume	Volume	Volume	Volume
			Time	Time	Time	Time	Time

Title

Mining Method Study Procedure



Alternative Options