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

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This paper reports the first stage of a study of the effects of low gravity (such as on the Moon and Mars) and microgravity (on asteroids and comets) on the efficacy of several representative terrestrial mining methods. The purpose is to evaluate their adaptability for use in space. Future papers will report on the effects of inimical or no atmosphere, and of other environmental aspects of mining in space, using a similar procedure.

The mining methods were first broken down into their component unit operations, which were then classified according to their gravity dependence. Secondly, the nature of the gravity dependence will be evaluated to determine whether, and how, the required gravity effects could be replaced to achieve similar results. This may require changes to other unit operations that do not themselves require Earth gravity for nominal operation. The third stage will re-formulate the mining methods for space use, and predict their efficiency relative to each other using carefully formulated simulations. Finally, the knowledge gaps made apparent by the exercise will be tabulated to form the basis of a research roadmap. This paper discusses the results to date of the study.

Introduction

AT PRESENT, humanity is confined to a single planet, at the mercy of many hazards. Some are of our own making – nuclear conflict, bio-weapons, environmental degradation – and due to our increasing impact on our environment. Some are dangers we cannot control – externally forced climate change, new diseases, and asteroid impacts, for example. Our long-term survival in spite of all of these will be enhanced when the Earth is no longer our only home.

Colonizing space, though, will not be easy. The major barrier to space exploration, the first stage of colonization, is the immense cost of escaping from the Earth's gravity. Although launch costs are decreasing (from $18,158/lb in 1990 to $11,729/lb in 2000 [Futron, 2002] and to $10,476 in 2009 [FAA, 2009] with $500/lb "achievable" [Musk, 2004]), the significant energy requirement (62.5 MJ/kg)[2] will likely keep them high for the foreseeable future. Therefore, reducing the mass of supplies and equipment launched from Earth is paramount. This requires incorporating non-terrestrial materials and products made with them in the exploration and colonization efforts as much as possible. As stated in a combined NASA-academia-industry report to the National Research Council (Sanders *et al*., 2005):

> The purpose of In-Situ Resource Utilization (ISRU), or "living off the land", is to harness and utilize space resources to create products and services which enable and significantly reduce the mass, cost, and risk of near-term and long-term space exploration. ... Today, missions must bring all of the propellant, air, food, water and habitable volumes and shielding needed to sustain the crew for trips beyond Earth. Resources for propellants, life support, and construction of support systems and habitats must be found in space and utilized if humans ever hope to explore and colonize space beyond Earth.

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[2] $U = \frac{GM_E m}{R_E} = \frac{(6.673\times10^{-11})(5.97\times10^{24})(1\,\text{kg})}{(6.378\times10^{6})} = 62.5\times10^{6}$ joules/kg

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Yet mining methods developed on Earth are not likely to be successful off Earth without modification (Boucher and Dupuis, 2001; Gertsch and Gertsch, 1990a and b). This is because mining was developed by human laborers under constant-direction gravity of 9.81 m/s^2, in an atmosphere of 78% nitrogen and 20% oxygen at 101 kPa pressure and temperatures of 210 to 310 K. There are major differences between Earth and other solar system bodies in terms of gravity, atmosphere composition and pressure, radiation levels, micro-impact hazards, temperature, and ease of access. These are the conditions in which non-terrestrial miners – both robotic and human – will operate.

Research Objectives

The goal of the research program, of which this paper reports the beginning, is to support the sustainable exploration and eventual colonization of the solar system, by ensuring that appropriate mining techniques are available. This will be done by developing a comprehensive suite of mining methods based on previous terrestrial experience and adapted to the non-terrestrial environments as they are currently understood. Obviously, as more experience is gained in these new environments, these recommended approaches will of necessity evolve into variations and completely new methods. This research program is merely trying to shorten the development of space-qualified mining methods, by reducing the need to "start from scratch" by those not familiar with current art.

Mining Methods

The most crucial aspect of operating a successful mine is not technology, but how the entire operation is conceptually organized from start to finish. Achieving success beyond technology; it requires selecting the appropriate technology to deal with the available deposits, in the environment where they are found, in order to reliably produce a certain outcome; in short, it is system development.

Some evidence indicates that humans have been mining on Earth for 300,000 years (Verri et *al*., 2004). "Space mining" has garnered attention since before humans sent any hardware into space. Tsiolkovsky discussed it in 1926, and fiction writers started using it as a setting for stories and novels shortly thereafter (Cummings, 1931 [lunar mining]; Tubb, 1958 [asteroid mining]). Serious commercial space ventures are now attracting large investments (Soper, 2013).

Mining on the target bodies will be both like and unlike mining on Earth. NASA (and other space agencies) has persevered through many years of lean and unpredictable budgets to support the development of innovative ISRU technologies for use on the Moon and Mars (e.g., Caruso *et al*., 2008; Craft *et al*., 2009; Sanders and Larson, 2012; Skonieczny *et al*., 2013). More are in development for use on near-Earth asteroids (*e.g*., Parness *et al*., 2012). Yet the most crucial aspect of operating a successful mine, what remains common to all mines everywhere, is not technology, but ways of managing the entire operation from start to finish; in short, system development.

Few efforts have substantially addressed the issue of mining methods (production systems) for regolith beyond the technology system stage (*e.g*., Rapp, 2013). What almost all publications and discussions focus on is the topic of excavation technologies. While certainly important for practitioners in this field, it is only about 20% of the issue. Excavation is just one of the unit operations of mining. "Mining method" refers to the entire system. Mining methods plan the extraction operation in space and in time to produce the desired outcome.

To achieve this, multiple mining methods have continually evolved throughout human history to reflect changes in technology, and to deal with all the various conditions under which mineral deposits are found. The main conditions that govern what mining methods can be applied to non-terrestrial bodies are (Hartman and Mutmansky, 2002):

- Depth, overburden thickness, size, shape, mineralogy, structure, and spatial attitude of deposit;
- Magnitude and variability of concentration of the component(s) targeted for production;
- Mechanical properties of the surrounding and interspersed unwanted material, such as cohesiveness, rippability, hardness, abrasiveness, and density; and
- Properties that control the separation of the desired from the unwanted materials.

Between surface and underground mining methods – which differ most apparently in mode of access – there are differences also in the amount of unwanted material that must be excavated to reach and remove the target material (ore). The ratio of waste to ore handled (stripping ratio) is one indicator of the efficiency of a mining method. Near-surface deposits often can be mined by either surface or underground methods. As the deposit goes deeper, however, the stripping ratio increases and at some depth reaches an economic limit. At depths below that, underground methods must be brought into play. These require removal of much smaller rock volumes for access but may require that valuable ore be left behind. The degree to which this is required is reflected in the recovery, which is the proportion of the available target material that actually is recovered for use.

Ground stability control adds another level of definition for underground mining methods. These are classified according to the stress and strain fields induced in the near-field and far-field of the regolith mass by mining (Brady and Brown, 1992). In terrestrial practice the classifications are further subdivided on the basis of the means used to achieve their distinctions (below); these means include opening size and sequence, as well as technological aspects of accomplishing the unit operations. The details of the various mining methods that have been developed over the millennia will provide initiation points for the development of the mining methods in this project. The three main categories are (Gertsch and Bullock, 1998):

- Naturally supported, also called minimum support methods. These restrict displacements in the near- and far-fields of the in situ material mass to elastic orders of magnitude by increasing the elastic strain energy stored in local stress concentrations. For surface mines this means leaving less-than-vertical slopes (thus increasing the amount of waste to be mined). For underground mines it means leaving pillars of otherwise minable ore in place. Sudden, uncontrolled release of that strain energy is prevented by ensuring that the slopes and the pillars can withstand the stress concentrations, and that the near-field confining stresses remain sufficient to maintain the continuum behavior of the material mass.
- Unsupported, also called caving methods. The ore mass is induced to fail and is withdrawn through lower, stable access points. These exploit the discontinuous behavior of material induced when confining stresses are reduced. They prevent the accumulation of strain energy, by continuously dissipating the energy derived from the pre-existing gravitational, tectonic, and residual stress fields. The strain energy instead is expended in fracturing and rigid-body displacement of both near- and far-field material. This reduces the total potential energy of the material mass. The rate of energy consumption in the deforming material must be kept proportional to the ore production rate; otherwise, metastable structures can develop in the moving mass that interfere with the deformation field.
- Artificially supported, also called additional support methods. These produce particle displacements and strain energy fields intermediate between the previous two categories. In practice this is achieved through judicious timing and placement of engineered support equipment, and of waste material to back-fill mined-out voids.

The different properties of soil and rock affect the mining method used. Mining regolith instead of rock reduces, but may not eliminate, the need for primary fragmentation. On the surface, mining regolith lowers the maximum safe pit slope angle, in comparison to mining rock. Mining or tunneling in non-cohesive materials underground is difficult, due to their much lower strength, but is possible with sufficient support (exemplified on Earth by pipe-jacking, and the use of pressurized chambers for boring tunnels through sediments beneath rivers).

The boundaries between these three main mining methods categories will shift in accordance with the spatio-temporal variations of the properties of the target body (gravity magnitude and direction, material properties, thermal properties, *etc*.). Gravity is especially important. Lowering gravity reduces stresses in the materials and also lowers the amount of frictional resistance equipment can utilize. Both have major implications. Further, lack of an atmosphere can have substantial impact on any process that utilizes rapid expansion of gases. Caving methods, for example, will work in more familiar ways on Mars than on the Moon or especially a NEA, due to its stronger gravity.

Selection of candidate mining methods for a mineral deposit, whether on or off Earth, depends on a range of criteria. This is an important choice, as the development required for some mining methods precludes the use of others. The factors to be considered include:

- Production rate – to match the demand,
- Recovery – the proportion of *in situ* ore that is actually extracted,
- Dilution – the amount of waste inextricably produced along with the ore,
- Flexibility in response to changing conditions (such as average ore grade),
- Selectivity – ability to discriminate between ore and waste,
- Safety and maintenance – ground stability, and
- Sustainability – the ability to leave the surroundings in a condition suitable for future use.

The approach being followed is to break down terrestrial mining methods into their component unit operations, and to identify the technologies that are used to accomplish each of the unit operations. Then the technologies available or likely to be developed for use in space will be applied to the unit operations, from which potential mining methods will be assembled that can also satisfy the restrictions (and take advantage of the opportunities) imposed by the environments of other solar system bodies. Unusual approaches regarding mine layout and scheduling will be explored.

Target Solar System Bodies

Near-Term Targets

The targets that will be studied first are Earth's Moon, Mars, and near-Earth objects (NEOs). The environmental parameters that will affect mining methods on the Moon and Mars are well known, though those of NEOs are understood only conceptually (Heiken *et al*., 1991; refers).

Far-Term Targets

The Oort Cloud contains most of the mass of the solar system, and eventually can be expected to provide much of the raw geologic material for human civilization. However, between now and that time, the other terrestrial planets, the asteroid main belt, the moons of the gas and ice giant planets, and the trans-Neptunian objects intermediate between the planets and the Oort Cloud will provide significant opportunities for responsible mineral production. In addition to mining of solids, material production from liquids (*e.g*., organic compounds on Titan) and gases (from the atmospheres of the outer planets) will likely become important, which production methods may be based in current-art petroleum engineering.

Methodology

The procedure being followed is divided into several tasks, of which the first is currently underway.

Dissect Terrestrial Mining Methods

The first task is to break down terrestrial mining methods into their constituent unit operations, so that the objectives of those unit operations can be transferred to new situations. The investigation is not restricted solely to modern trends in mining, because some aspects of historical methods may be more easily applicable to space. Therefore, "obsolete" methods as described by Peele (1918 and 1941), Anonymous (1936), Jackson and Gardner (1936), Staley (1949), and Fritzsche and Potts (1954) are being reviewed in addition to more current references (Stewart, 1981; Kennedy, 1990; Hartman, 1992; Gertsch and Bullock, 1998; Hustrulid and Bullock, 2001; Darling, 2011; and others).

Regardless of historical status or location, all mining methods share several common unit operations.

Unit Operations

The fundamental unit operations of mining are fragmentation, excavation, transportation, and beneficiation.

Fragmentation is the first stage of comminution (further comminution, if needed, is done during beneficiation), and consists of detachment of the ore from its surroundings. This is easily visualized for mining of rock, and may be important for mining of regolith as well, due to its high level of compaction from long exposure to meteoroid impacts. Direct fragmentation of regolith may be required where ices or other minerals provide intergranular cement. The most energy-efficient fragmentation of competent material (rock) is from chemical explosives (which contain the oxidizer within their formulation, and thus do not require atmosphere), but mechanical means (e.g., tunnel boring machines, continuous miners, roadheaders, boomheaders, milling machines, plows, planers, rippers, etc.) can be effective as well if properly matched to the *in situ* material characteristics.

Comminution of the lunar regolith is especially problematic. The regolith's typical particle size is already in or near the size range that most modern milling practices attempt to reach. But the starting grain size of terrestrial ores is much larger than the grain sizes common to lunar regolith. Presumably, other regoliths formed through hypervelocity impacts will have similar characteristics. The amount of energy needed to reduce particle size increases as the particles become smaller.

Excavation is removing the ore from where it was fragmented. This may mean loading into a transportation system. Fragmentation, excavation, and transportation are often combined in one piece of equipment.

Beneficiation is a crucial step. Products such as bulk regolith for radiation protection can be used immediately thereafter, while others such as feedstock for structural material manufacture require additional processing and manufacturing. Beneficiation generally includes further comminution or even agglomeration (if needed) to the appropriate particle size for separation, and then separation of the waste from the target material(s). A wide variety of techniques have been applied to terrestrial ore separation (Wills, 2006). Some (*e.g*., electrostatic sorting) are more readily adaptable for use on the target bodies than others (*e.g*., classification, which requires fluids); however, the use of sparse gas streams in place of water may revolutionize the use of slurries in mineral processing.

Terrestrial Mining Methods

Mining methods can be categorized in various ways, starting with whether the deposit is accessed from the ground surface or from underground. These categories can be further modified by the overall mode of rock mass energy dissipation inherent in the mining process (Brady and Brown, 1992), applied to traditional categories such as those of Gentry (1992), Karmis (1992), Hartman (1992), and Hartman and Mutmansky (2002). Methods that rely on unique terrestrial properties are not included, such as hydraulicking, which uses large-volume water sprays for fragmentation, excavation, and transportation. The result is the following list of terrestrial mining methods:

- Self-supported mining methods
  - Surface Access
    - Open pit mining
    - Area mining
    - Auger mining
    - Borehole mining
    - Dry dredging
  - Underground Access
    - Shrinkage stoping
    - Room-and-pillar mining
- Artificially supported mining methods
  - Underground Access
    - Stull stoping
    - Cut-and-fill stoping
  - Underground Access
    - Square-set stoping
    - Sublevel stoping
- Caving mining methods
  - Underground Access
    - Block caving
    - Sublevel caving
    - Longwall mining
  - Underground Access
    - Shortwall mining
    - Top-slicing

Characterize Non-Terrestrial Mineral Deposits

The second step is to develop a database of extra-terrestrial deposit types and their characteristics pertinent to resource utilization. This will be based on current understanding of planetary processes that are known, or expected, to concentrate potential ores[3], and on forecasts of the materials needed at the various stages of space exploration. Both sides of the demand-supply relationship will be dealt with.

Supply-Side

Deposit-forming processes are those that concentrate a desired material at levels above the average for that body or class of bodies. The variety of potential ore formation mechanisms in space is extensive (Hartmann, 1985; Lewis, 1995). Each class of solar system bodies will be associated with its own suite of deposit-forming processes, though some processes may occur in several classes. These processes are important to identify and exploit because direct usage of undifferentiated raw material is feasible only in special cases. Segregation that has not been accomplished by natural processes generally has to be finished by artificial ones.

Many of the igneous and metamorphic deposit-forming processes active on the other terrestrial planets will be familiar from terrestrial experience, though different styles of tectonics may alter their occurrence (Schubert *et al*., 2001).

Demand Side

Water will be a precious commodity for space exploration and, eventually, space colonization. In addition to water, different raw materials are needed at each stage of exploration because early activities demand a different suite of materials than later activities (Sullivan and McKay, 1991).

The earliest NASA missions for whom mining technologies must be at least implicitly selected may be robotic exploration missions. Some may be shared with commercial and/or international partners. These missions will progressively demonstrate, field-test, and scale up crucial technologies in situ before humans arrive. Important products from early mining missions include bulk regolith for radiation and exhaust-blast shielding and as feedstock

[3] An orebody is a material deposit that can be mined for a net benefit; thus not all deposits are orebodies.

for propellant and life-support gas production, as well as spaceship propellants manufactured from lunar materials. This will strengthen the ability to go on to Mars, as well as to explore the Moon itself.

Develop New Mining Methods

The unit operations will be reconstructed into new mining methods for the deposit types identified for the short-term target bodies, as shown in Figure 1. Between three and ten basic methods are expected to be sufficient to address them all, at this relatively broad conceptual level. The exact number will depend to a large extent on how many different deposit-formation mechanisms are identified, since the same general mining method can be applied to deposits formed by similar mechanisms on different bodies.

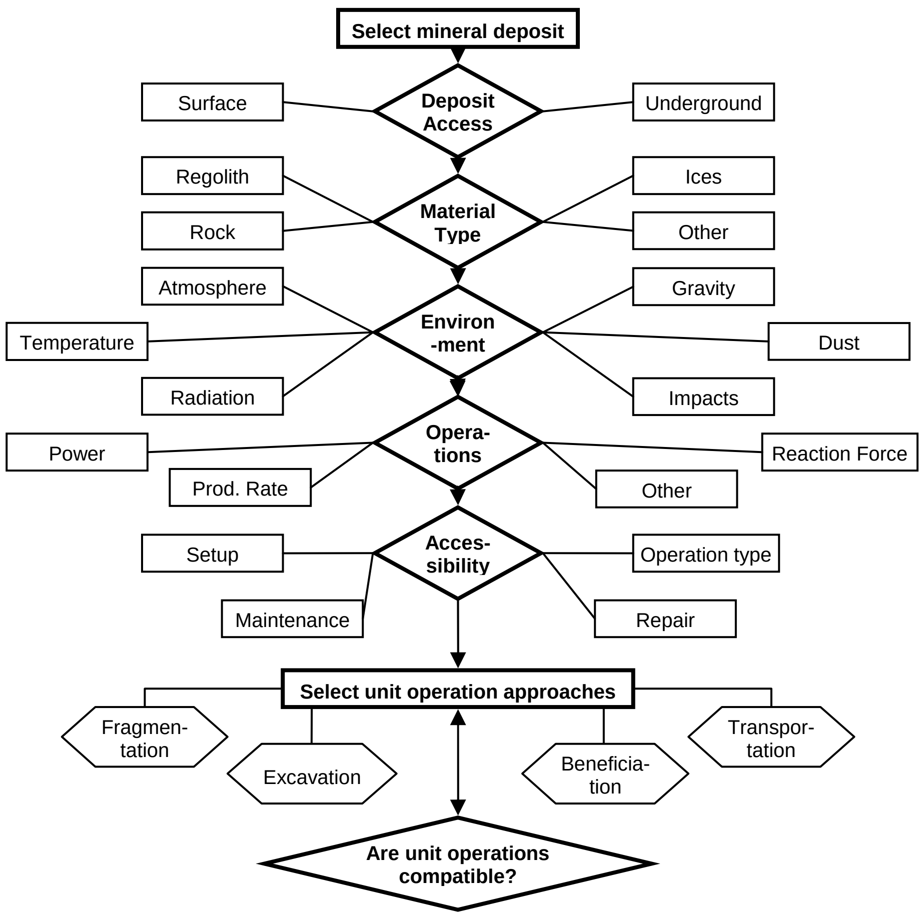


Figure 1. Procedure for development of a new mining method.

Evaluation of the pertinent properties of the deposit type will lead to selection of feasible technological approaches for the unit operations. These approaches must be compatible with each other as well as suitable for the specific non-terrestrial environment. Compatibility options will be iterated until a notionally feasible mining method has been outlined. The iteration will be non-trivial, since traditional methods for achieving the unit operations can be supplemented by new approaches that take advantage of one or more features of the target body environment.

Evaluate Mining Methods Using Simulation

Determine the feasibility of the new mining techniques through discrete simulation, since appropriately scaled field trials that accurately simulate lunar or asteroidal mining conditions are impractical.

Discrete simulation is routinely performed on Earth as a supplement to field trials, although it is not generally used to evaluate complete mining methods in new environments or new types of mineral deposits. Where previous experience in the deposits or the environments is lacking, however, it can be the only option available to evaluate potential choices. Extra-terrestrial “mining” experience is limited to very small trench-digging (Curiosity, Spirit, Opportunity, and Sojourner rovers; Phoenix, Viking, and Surveyor landers; Apollo astronauts), rock surface grinding (Curiosity, Spirit, and Opportunity rovers), and shallow drilling (maximum depth 3.2m, Apollo astronauts [Carrier, 1974]) in regolith. Only a very small sample of asteroid regolith has been collected directly (Tsuchiyama *et al*., 2011).

This task starts by designing a specific extraction plan for a representative regolith deposit. Each potential mining method is evaluated by setting up a mine layout and a schedule that appear likely, neither random nor optimized. The deposit parameters will be either deterministic or stochastic, as appropriate for the property (Journel and Huijbregts, 1978). The scarcity of precise data for most of the parameters and the actions to be modeled precludes optimization at this point.

Results to Date

The procedure described above was begun with surface mining methods suitable for unconsolidated or cemented regolith. Water ice deposited between the regolith grains is likely to be the first mining target in space, so the first terrestrial mining methods to be studied are those that have evolved for producing near-surface horizontal coal seams, alluvial sand and gravel, or crushed stone. Figure 2 illustrates a typical operational sequence.

Site preparation refers to creating access-ways to the minesite designed for the duration of mining, as well as setting up / bringing in basic utilities (power, water, *etc*.). In addition, at a site that has not been previously developed, the topsoil (if any) is removed and cached for replacement during mine closure and reclamation. However, Earth is the only place currently known where this step is required. Scientific investigations, though, which on Earth most often mean detecting, identifying, and inventorying any traces of previous cultural activity (archeology), will likely be an important and ongoing activity in space mining for quite some time. This need for scientific data appears to conflict with the long-term mining industry habit of strict project confidentiality, but hybridization with “new space” entrepreneurship may modify this in the space mining industry.

Overburden – material of little or no value that overlies the ore zone – is expected to exist in relation to regolith-hosted ice deposits, so it must be removed first. This is where the mine phasing comes in; it usually is more cost-effective to mine an orebody in phases rather than all at once, depending on its size. Overburden stripping (removal) is often done significantly ahead of the actual mining. The information gained during stripping then informs planning of the extraction phasing.

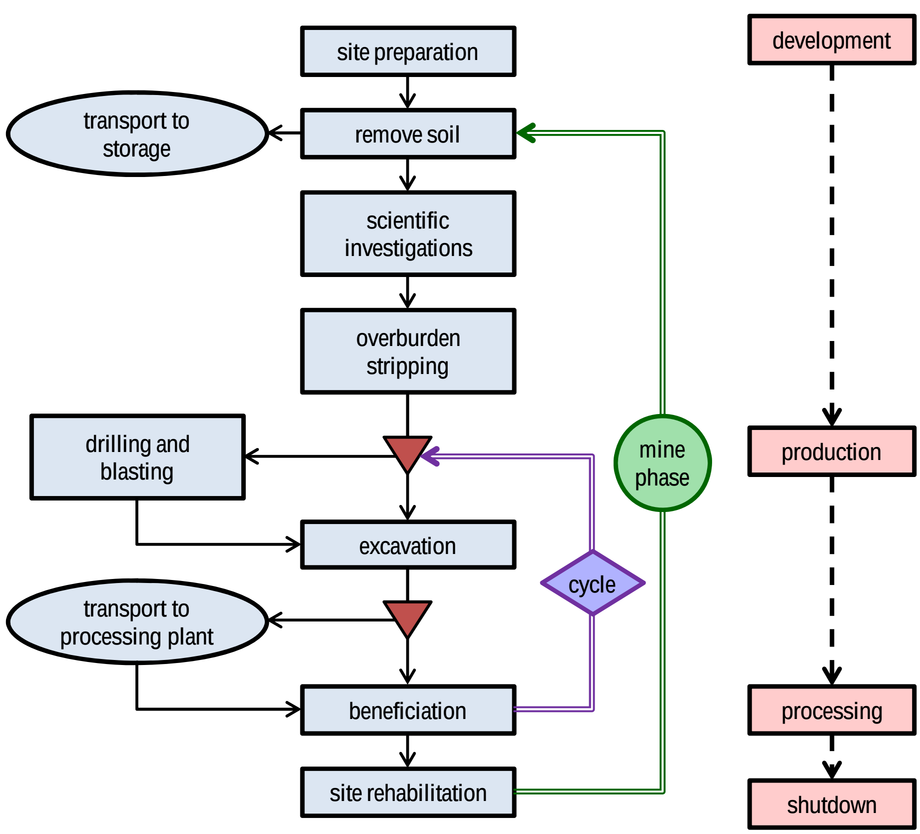
Figure 2. Typical terrestrial surface mine operations sequence.

Of the unit operations, fragmentation and excavation are the most often combined, usually in mechanical equipment. Explosive fragmentation is an alternative that includes compressed gas technologies in addition to blasting agents. The cycle of fragmentation – excavation – transportation – beneficiation is repeated as often as necessary to complete each mine phase.

At this point, the research is identifying the gravity dependences of the unit operations. These include direct effects, which are those most commonly cited in the literature, and indirect effects, which will not become apparent until new or modified mining methods have been developed and simulated. Those identified to date are listed in Table 1; more are in process.

Table 1. Some effects of gravity in mining unit operations.

DIRECT EFFECTS:	
excavation forces	drilling weight-on-bit (thrust)
	excavator bite (penetration to initiate chipping)
	bucket/blade fill
blast casting	combined fragmentation, excavation, and transportation
materials transport	conveyor capacities
	sparse-gas slurries for pipe flow
general transportation	ground contact properties
	slope angles
INDIRECT EFFECTS:	



modified terrestrial mining methods	relative contributions of gravity-affected parts of unit operations will vary with body
	aggregate time/energy distributions will vary with body
new mining methods	may result from environment-based innovations

Excavation Force Requirements

For ease of comparison, excavation forces are resolved into horizontal and vertical components with respect to the ground surface, or to the geoid if the body is small. Terrestrial mechanical excavators derive vertical force mainly from the weight of the machine, and horizontal force from its traction or, again, its weight. There are situations where either or both are supplemented by anchoring. Explosive excavation, as well, can be designed to displace the fragmented material horizontally as needed. This is termed “blast-casting”.

Wilkinson and DeGennaro (2007) reviewed the most commonly used equations for mechanical excavation. Though based on fundamental principles, these equations are empirical and thus difficult to extrapolate to non-terrestrial conditions. Nevertheless, some could be recast with gravity as an explicit independent variable. Figures 3 through 5 illustrate the range of values they give for gravity magnitudes up to 10 m/s^2. The surface gravities of Earth, its Moon, Mars, and asteroids are marked on the charts. Figure 3 shows the required horizontal force component for regolith excavation, which Figure 4 shows the required vertical excavation force. Figure 5 then shows the force available for a generic machine, assuming a ground pressure of 5 kPa and a mass of 700 kg.

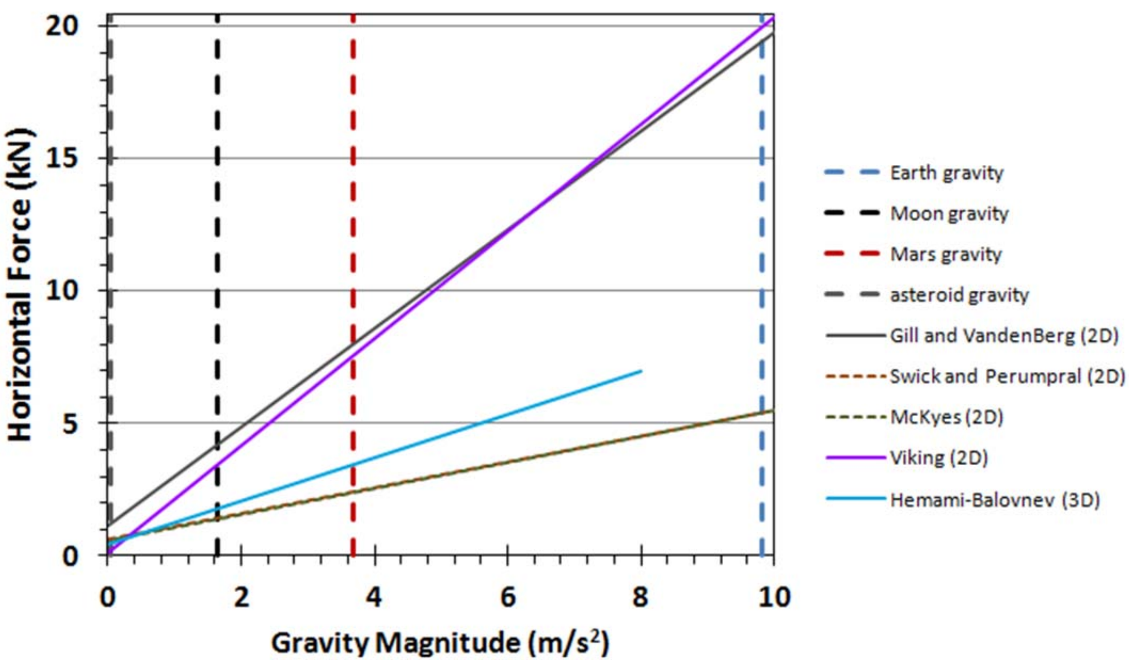


Figure 3. Horizontal force required for blading regolith, as a function of gravity. See Wilkinson and DeGennaro (2007) for details of the named equations.

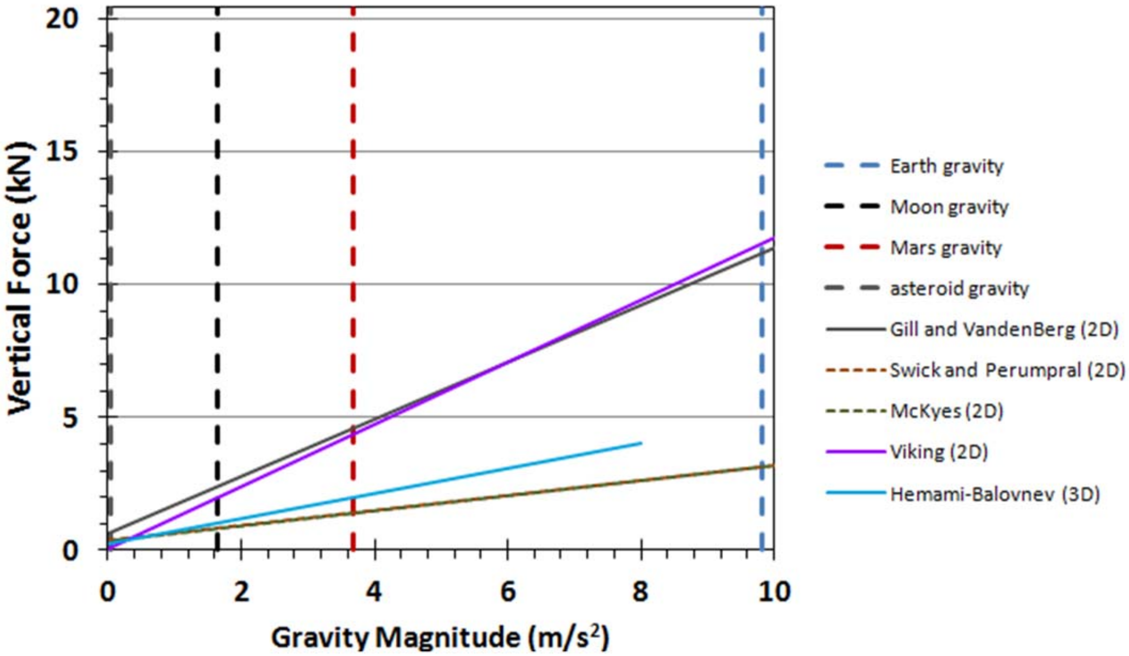


Figure 4. Vertical force required for blading regolith, as a function of gravity. See Wilkinson and DeGennaro (2007) for details of the named equations.

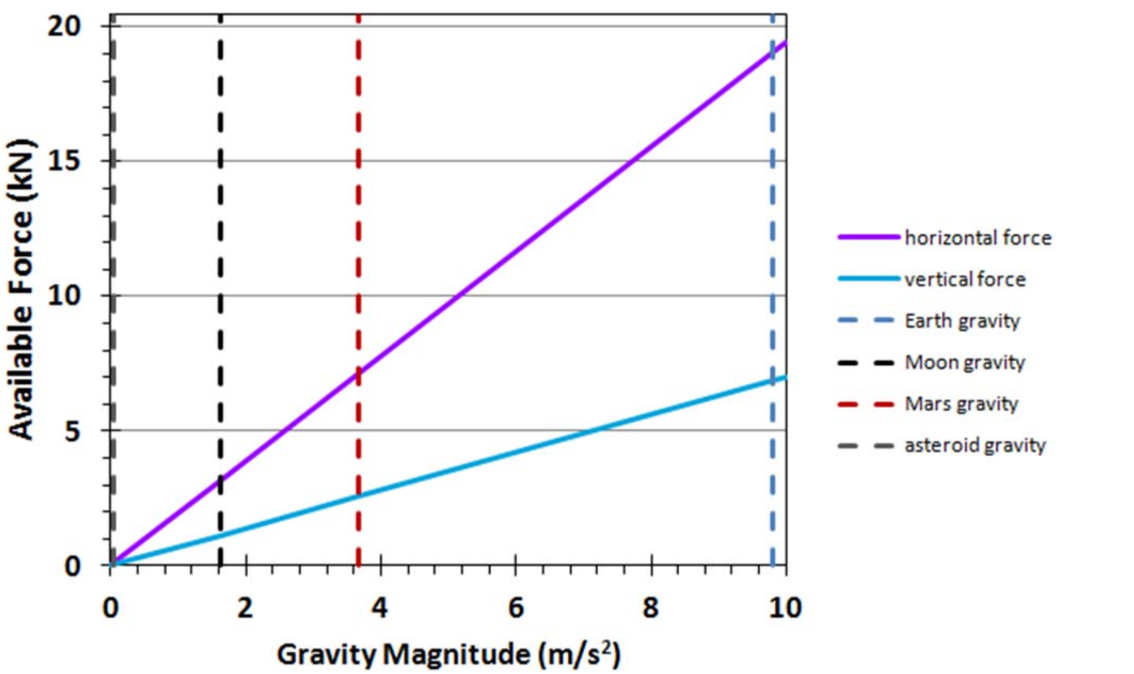


Figure 5. Horizontal and vertical excavation forces available on a regolith surface, modeled for the lunar case. See Wilkinson and DeGennaro (2007) for details of the calculation.

Conveyor Force Requirements

Conveyors are ubiquitous in terrestrial industry, from mines to farms and factories. Of the several types, tension-drive belt conveyors are the first to be examined in this project. Belt conveyors are very complex systems (Figure 6) which behavior is proving difficult to predict under different gravity regimes. The flow behavior of the transported material is only part of the issue. Gravity effects of the equipment itself are, in addition, highly dependent on the compliance and friction factors of the material covering the drive pulleys, the belt material, the idler material, the bin and chute material, and also the bearings in the pulleys and idlers.

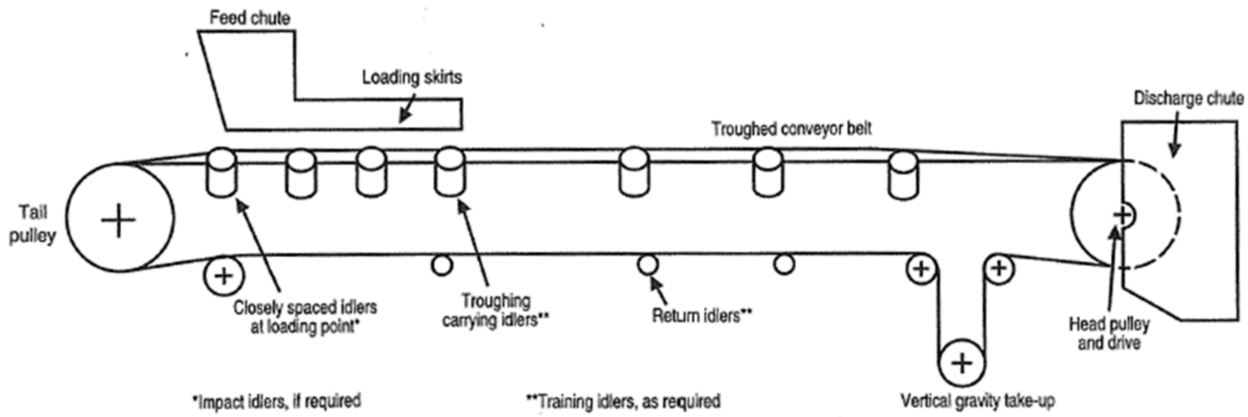


Figure 6. The basic parts of a belt conveyor (CEMA, 1997).

Material Storage

It is likely that the bulking factor of regolith and rock when fragmented may vary inversely with the gravity magnitude, though the relative significance of the variation remains to be determined. Terrestrial values of the difference in volume associated with the change from undisturbed to fragmented state are usually 20-50%, and seldom less than 5%.

The low-level but very long-term impact vibration compaction of regolith on airless bodies is a mechanism with which we have little experience. It is likely that, in place of the moisture-mediated soil behavior that is common on Earth, material disturbed from this long-term equilibrium will behave similarly to cohesionless loess deposits that are not easily compacted. Thus the effects of lower gravity may be overcome by other effects of the environment. Sintering is one approach being tested to mitigate this possibility, as well as to prevent the spread of abrasive dust (Taylor *et al*., 2005; Álvarez *et al*., 2012; Nakamura *et al*., 2012); it may have to be widely used to prevent increasing sinkage, slipping, and loss of traction with ground surface wear in trafficked areas.

Conclusions and Future Work

Though the research is in a stage too early to reach true conclusions, expectations are forming that the effectiveness of mechanical fragmentation and excavation may lie less in using brute force derived from machine mass, and more in finesse made possible by advances in equipment control techniques. Such finesse has been considered the sole province of human intellect, but non-traditional robotics approaches and those that combine human interaction with semi-autonomous systems may provide alternatives not previously considered.

The indirect effects of gravity on combinations of unit operation technologies into mining methods may be non-intuitive, as well. These determinations will begin in earnest when the direct effects of gravity and other aspects of non-terrestrial environments are better characterized than at present, and their combined effects can begin to be explored.

An important set of questions has arisen during the investigation to date: What are the properties of materials yet to be developed for use in space? This is in addition to incomplete understanding of the properties of presently existing materials when used in space. Determining the relative effects of gravity on equipment depends on knowledge of the rigidity, density, and friction coefficients, at a start, of the materials of which it is made. It is hoped that such characterizations will proceed at a faster pace than they are currently.

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