MINING ASTEROIDS VERSUS MINING THE MOON – CAN YOU HAVE YOUR CAKE AND EAT IT?

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Introduction: Near-Earth asteroids (NEA) are an attractive target for exploration and resource appropriation as they are relatively accessible. Traditionally, asteroids have been coveted as sources of mineral wealth – siderophilic platinum group metals (PGM) including Pt, Os, Ir, Ru, Re, Rh, Mo, Nb, Ta, Zr, Ge, W, V [1] – and water to be used as propellant. It has been estimated that only 1 in 2000 NEOs (~10) have high enough concentrations of PGM and only 1 in ~1000 NEOs (~20) have high enough concentrations of water to be economically mineable on NEOs with low $\Delta v<4.5$ km/s and diameter >100 m (~20,000 NEOs) [2]. This suggests that these resources must be regarded as finite and even scarce. We review asteroid resources with a view to determining whether their constituent materials are useful as propellant, structural metals, refractory oxides, water and other volatiles for the construction of space infrastructure [3,4]. Most materials require accessing different classes of asteroid with a wide range of distances and orbital periods. Some however will be available on all asteroid types such as troilite constituting 5% of ordinary chondrites, 1% of carbonaceous chondrites, 0-5% nickel-irons and 5-10% of enstatites. Chondrites are characterised by chondrules, mm-sized globules embedded within a fine-grained matrix. Both chondrules and matrix are dominantly ~30-60% olivine and ~15-30% pyroxene (dominated by orthopyroxene) in ordinary chondrites [5], e.g. enstatite ($Mg_2Si_2O_6$).

Broad asteroid/meteorite compositions: S-type meteorites are primarily silicates, dominantly olivine (Mg_2SiO_4), with $6>MgO/Fe_2O_3>0.2$. M-type asteroid composition is 70-95% Fe – 5-30% Ni – 0.2-2% Co, 0.5-2% S, 0.1-0.5% P, <0.05% Ti, Cr and Mn, 0.006-0.02% Cu [6]. Troilite is the most abundant accessory mineral in iron and other metal-rich meteorites with a 10-20% abundance [7]. Carbonaceous chondrites have a high carbon content including carbonates (calcite, dolomite and magnesite) and organics. They possess hydrated minerals such as phyllosilicates (clays) including serpentines, montmorillonite and talc.

Carbon Resources: CI, CM and CR carbonaceous chondrites are richest in carbon ~2-5% C and N ~500-2000 ppm [8]. Around 60-70% of the carbon is insoluble kerogen [9] and around 30-40% is a soluble mix of organics [10]. Heating the organic fraction of carbonaceous chondrites at 700ºC will release organic volatiles that may be oxidised in O_2 to CO_2. CO_2 with H_2O provide the basis for manufacturing syngas ($CO + H_2$). The manufacture of space-rated plastics such as BoPET and PEEK and high utility plastics such as PMMA and PVDF require complex chemical processing, rendering them unlikely in the near-term. The most significant use of carbon is as a source of graphite and CO_2/CO/CH_4. CH_4 is a non-cryogenic propellant.

Iron-Nickel-Cobalt Resources: Iron-nickel-cobalt are metals in metal-rich stony chondrites and M-type asteroids. CO is required for the carbonyl (Mond) process for extracting Fe, Ni and Co [11]. Gaseous CO reductant provides gaseous carbonyl separation through fractional distillation. Nickel-iron alloy is heated with CO to 110ºC and 0.1 atm to form gaseous iron and nickel carbonyls in the presence of S catalyst. They are separated by fractional distillation and further heating to 200ºC releases CO and deposits pure metal separating out Fe, Ni and Co.

Water Resources: Water in asteroids is in hydrated mineral form with CM and CI comprising 10% water and CM indicating phyllosilicates with an average water concentration of ~7%. For carbonaceous chondrites, the extraction of water from hydrous minerals such as gypsum ($CaSO_4.2H_2O$) require high temperatures up to 600ºC, far in excess of that for water ice sublimation on the Moon.

Aluminium Resources: Calcium-aluminate inclusiona (CAI) are ≤mm- to (more rarely) cm- sized particles of Ca-Al-Mg-Ti oxides and silicates comprising <5% chondrule mass [12]. Aluminium abundances given by Al/Si ratio are approximately constant within classes – 0.087 in carbonaceous chondrites compared with 0.061 in ordinary chondrites [12]. Hence, Al is depleted compared with the Moon. Abundant lunar anorthite can be readily processed to yield the multifunctional aluminium metal [13,14].

Copper Resources: Cu is found in most meteoritic groups including ordinary chondrites contained within FeNi alloy at 70-100 ppm [15] but is slightly more abundant in carbonaceous chondrites at 130-250 ppm [16]. It is considered highly rarified.

Sodium Resources: Na_2CO_3 permits growth of piezoelectric quartz from silica for sensors [29]. In ordinary chondrites, primary calcic plagioclase converts to sodic plagioclase (albitisation) during thermal metamorphism through fluid interactions [17]:

$$\underbrace{2CaAl_2Si_2O_8}_{\text{anorthite}} + 2SiO_{2(aq)} + Na_2O_{(aq)} \rightarrow \underbrace{2NaAlSi_3O_8}_{\text{albite}} + 2CaO_{(aq)} + Al_2O_{3(aq)}$$

Albite is a source of both Na and Al. Na is also depressed in stony meteorites exhibited by Al/Na ratio which varies from 1.4-3.3 in carbonaceous chondrites and 1.45 in ordinary chondrites [12]. Plagioclases are quite rarified ~8% of ordinary chondrites compared with high incidence of pyroxenes and olivines.

Halogen Resources: Extraterrestrial halogens such as Cl are rarified because of their high volatility – Cl abundance in chondrites is nominally ~100 ppm [18]. Cl is crucial as a ubiquitous reagent (HCl).

Selenium Resources: The concentration of selenium in ordinary chondrites is ~8-12 ppm [19] due to $Se/S \approx 4.0 \times 10^{-4}$ in FeS [20]. Selenium is an optically-sensitive semiconductor but it may be substituted with FeS_2 which may be derived from the much more common FeS ~10% in M-type meteorites [21].

Tungsten Resources: Tungsten is crucial for vacuum tube technology. Tungsten concentration is concentrated in metal so in iron meteorites has been measured at 0.07-5 μg/g (averaging 1.2-2.1 μg/g) similar to that of Pt, i.e. ~ 1 ppm [22]. This is highly depleted compared with lunar tungsten averaging ~500 μg/g.

Lubricant Resources: Lubricants are essential for rotating machinery such as electric motors and drills. The hydration of the pyroxene enstatite yields talc:

$$\underset{\text{enstatite}}{6MgSiO_3} + H_2O \rightarrow \underset{\text{serpentine}}{Mg_3Si_2O_5(OH)_4} + \underset{\text{talc}}{Mg_3Si_4O_{10}(OH)_2}$$

Talc may be employed as a dry lubricant as an alternative to tungsten or molybdenum disulphide [23]. More generally, pyroxene may be processed with hot HCl to yield montmorillonite and solutions of silica and iron oxide:

$$CaFeSi_2O_6 + HCl + H_2O \rightarrow Ca_{0.33}(Al)_2(Si_4O_{10})(OH)_2.nH_2O + H_4SiO_4 + CaCl_2 + Fe(OH)_3$$

Montmorillonite is an expanding clay that is the primary ingredient in bentonite: (i) viscous agent in drilling mud (ii) binder in sand casting - green sand is sand mixed with bentonite clay and water. This last capacity as a binder offers the potential to replace polymer binders in extraterrestrial 3D printing (TBD).

Asteroids on the Moon: Asteroids offer a unique inventory of resources unavailable on the Moon but asteroidal resources on the Moon are too diffuse to be mined. Concentrated resources have been deposited into the Moon's surface by impacts [24] with metals indicated by magnetic anomalies [25] and C and N-rich deposits [26]. Orbital magnetic survey of the SPA could not penetrate >10 cm to detect Fe resources [27] buried under 4.3 By of impact gardening.

Conclusions: Asteroids are repositories of crucial materials required to support an industrial ecology especially ferrous Ni and Co metals, troilite (FeS), volatiles involving C and N, [28]. If such sources can be located on the Moon, the Moon would provide the material resources to support a full industrial ecology without reliance on an Earth-based supply chain.

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