ORE MINERALS, THE MINERALOGICAL BARRIER, AND THE ELEMENTOME IN SPACE. K. M. Cannon[1,2], [1]Department of Geology and Geological Engineering, Colorado School of Mines. 1301 19th St, Golden CO 80401. [2]Space Resources Program, Colorado School of Mines. Email: cannon@mines.edu.

Introduction: Most of the tangible resources sourced from space will ultimately come from regolith and ices. There are some simple applications using raw or slightly processed regolith–what would be called "industrial minerals" on Earth–such as berms around landing areas or gravel roads. But most all other applications (solar cells, wiring, fission fuel, etc.) require individual chemical elements like Si or Cu to be extracted in relatively pure form, sometimes before recombining them as compounds.

Previously, the space resources community has not applied rigorous thinking in considering which elements might be extracted from regolith and ice on various planetary bodies. It has been common practice to use bulk chemistry as an argument for whether elements can be extracted, to underestimate the difficulty of beneficiating fine-grained regolith in dry conditions, and to argue from simple analogies to Earth: for example, we extract element X from terrestrial rocks using process Y, so the same must be possible for the Moon or Mars. In this presentation I will provide analyses to properly treat the problem of extracting pure elements based on how much energy is available at one's disposal.

Ore Minerals: Only 19 chemical elements occur on Earth in their pure, native form. At present, few of these are economically mined from these occurrences: C and Au, and sometimes Ag, Hg, Pt, and As. All other elements occur in the form of minerals with multiple elements bonded strongly together, or as mixtures (e.g., brines, atmospheric gases). There are currently 5,863 mineral species recognized by the International Mineralogical Association, but only a small subset of about 150 are economic to mine: these are the "ore minerals". For example, chromite ($FeCr_2O_4$) is the only ore mineral of chromium, while copper has about a dozen ore species including chalcopyrite ($CuFeS_2$) and bornite (Cu_5FeS_4). No formal definition exists for what constitutes an ore mineral, but by compiling a full list of these species some commonalities emerge. Ore minerals must contain the element of interest (usually making up a high proportion of the mineral's mass), and they tend to have very few other essential elements in their chemical formulas. An analysis shows that ore minerals have on average just 2.6 essential elements in their formulas compared to 4.5 for all minerals. Other features in common are a tendency toward higher symmetry, and toward anisodesmic crystal structures which makes sense given the goal of ripping away one element of interest from all the others.

An original compiled list of ore minerals was compared against minerals reported from space materials including meteorites, returned samples, and remote sensing. For the 45 elements that have terrestrial ore minerals, 29 (64%) have none of these minerals reported in materials from any planetary body (Fig. 1). However, 6 of these 29 (F, Co, Au, Al, S, and Th) have potential alternative sources. For example, none of the terrestrially used ore minerals for Al are known to occur in space, but Al could be sourced from widespread anorthite on the Moon [1,2], rare patches of kaolin-group minerals (halloysite?) on Mars [3], and from hibonite or spinel in L-type asteroids [4]. The remaining 23 elements have no terrestrial ore minerals known from planetary materials and no clear alternatives.

The fact that many elements are mined as by-products on Earth does not help here: these by-products generally come from the ore minerals of more abundant elements, and if these minerals are absent then prospects for the by-products are low (Fig. 2).

The Mineralogical Barrier: Pure elements can be extracted on Earth at relatively low energy costs because ore minerals exist. These ore minerals are separated from the run-of-mine ore using mineral processing/beneficiation which uses low-energy grain sorting techniques to form a concentrate; the element of interest is enriched often by orders of magnitude in concentration before going to the smelter.

Skinner [5] anticipated a future where ore deposits become depleted and introduced the concept of the "mineralogical barrier". For geochemically common elements like Si or Fe the depletion is not a large concern and, counterintuitively, once lower grade deposits are opened up (at higher energy cost), there is much more ore available. But for geochemically scarce elements the depletion means ore minerals no longer exist and the low-energy path to extraction is eliminated. This creates a large jump in energy costs to extract lattice-bound elements in trace concentrations.

Because ore minerals are scarce in planetary materials, it is likely the mineralogical barrier is actually the starting point for most elements sourced from space. Without an immense amount of energy available to run a giant mass spectrometer or calutron, these elements will not be extracted in pure form. For example, it takes about 13–15 kWh to produce 1 kg of Al on Earth using mineral processing then smelting. But if

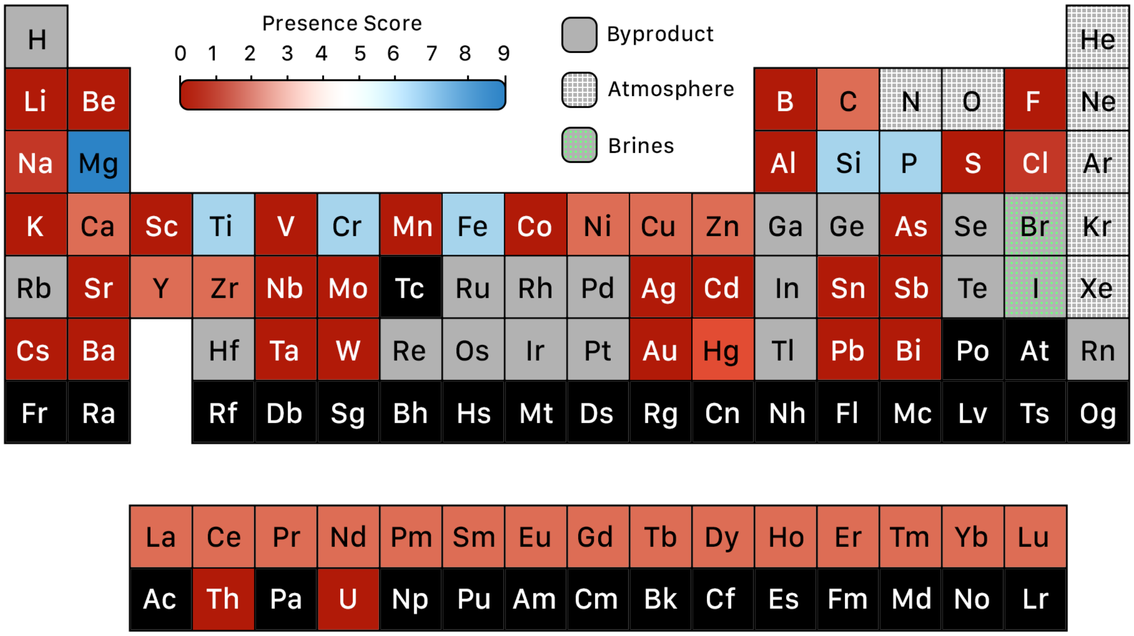

Fig. 1. The prevalence of ore minerals (or alternatives) in planetary materials (average of Moon, Mars, asteroids).

we were forced to use something like a calutron to extract Al from material lacking in Al minerals, the energy costs may be as high as 250,000 kWh per kg! There is a small reprieve here in that techniques like molten regolith electrolysis (MRE) can form metallic melts that can be poured off. However, this is probably only practical for the elements Fe, Si, and Al from typical lunar or martian regolith. Al from MRE might incur about 80 kWh per kg.

The Elementome: The "elementome" has been introduced to refer to the complete set of chemical elements used by a particular species. This idea began in ecology [6] but has since been applied to humans to study how our own species uses the elements of the periodic table. Recent research has shown we rapidly expanded our elementome to now use basically every naturally occurring element [7].

In a similar vein one can ask what elements will be produced from the Moon or Mars. Short of a dramatic increase in energy available, the list of pure elements extracted on the Moon is likely quite short: O, Al, Si, and possibly H at the poles, with Fe and Ti in mare regions. On Mars this may expand to include C, N, Cr, Cu, S, and Ni that have more promising sources. Will these planetary elementomes increase over time like they did on Earth? Perhaps, but there is also a strong trend recently toward "Earth abundant materials", in other words using advances in chemistry and advanced manufacturing to create products from elements like Fe and Mg that are abundant in the Earth's crust, rather than using rare, difficult to mine, and unsustainable elements like rare earths and platinum group metals. Advances in this area may happen fast enough that we do not need to figure out how to get harder to source elements in space.

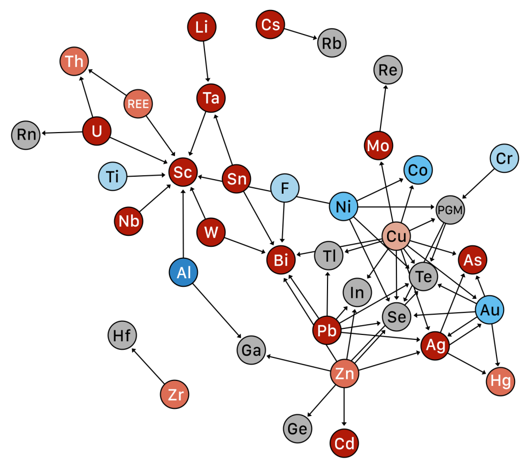

Fig 2. Elements commonly sourced as by-products.

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