INITIATING A USGS ASSESSMENT OF ASTEROID MINERAL RESOURCES.

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Introduction: The "Spurring Private Aerospace Competitiveness and Entrepreneurship Act of 2015," signed by the President on November 25, 2015, gives the Executive Branch 180 days to provide a report on space resources. In 1879, Congress mandated that providing mineral assessments within and beyond the borders of the Nation is the responsibility of the U.S. Geological Survey (USGS). Here we report how the USGS, with colleagues at other institutions, is taking steps to provide an initial assessment of the mineral resources within asteroids.

We have chosen to focus on three of many potentially useful resources: platinum, water, and native metals. Platinum has garnered the most public attention with published reports that asteroids will provide trillions of dollars in return for the investment in asteroid mining infrastructure [1,2]. Water from asteroids has the potential to dramatically reduce the cost of long-term human presence beyond Earth orbit as a source of drinking water, radiation shielding, oxygen to breath and rocket fuel [2,3]. Native metal has been demonstrated to be directly usable in 3D printing to form complex parts. The procedures and tools we are developing make it straightforward to do similar assessments of any other asteroidal material.

To further constrain the scope of this initial assessment, we have focused on the 2030-2050 time frame with human missions to Mars. While a self-sustaining economy may eventually be possible within the main asteroid belt, investigating such scenarios is beyond the scope of this preliminary report.

USGS Mineral Resource Assessments: The USGS provides assessments of mineral and energy resources across the Earth for use by governments, industry, and the general public. Over a period of many decades, the USGS has developed a methodology that has proven to be reliable and unbiased. Furthermore, the format of the assessment strikes a balance between simplistic and quantitative that has proven useful for decision making. The assessment consists of five models that are combined through Monte-Carlo methods to provide estimates of the minimum mass of a given resource at the 90, 50, and 10% confidence levels [4]. Adapting this methodology for asteroid resource assessments is the primary goal of this initial assessment.

Descriptive Models of Asteroid Resources: The first part of an assessment is to describe the geologic settings in which concentrations of the relevant resource can be found. Each geologic setting on Earth has a characteristic mineral assemblage. For asteroids, this is most similar to the meteorite classes. To link meteorites to asteroids, we rely on the SMASS spectral taxonomy [5]. For this initial assessment, we simplify the problem by only considering the 3 main spectral categories (C, S, and X). We further simplify matters by equating C asteroids with carbonaceous chondrites, S asteroids with other chondrites and achondrites, and X with iron meteorites. As discussed later, refining these simplifying assumptions would be the main focus of any follow-on assessments.

Spatial Model: The second model is the "spatial model" which describes where ore bodies can be found within boundaries set by political and technical limits. In our case, each asteroid can be thought of as an ore body. Given the 2030-2050 time frame, we limit this initial analysis to near Earth asteroids (NEAs) that can be reached from low Earth orbit with a Δv of ≤7 km/s.

Deposit Density Model: The third, "deposit density," model is used to determine how many deposits (i.e., asteroids) are in the study area. This part of the assessment takes advantage of activities driven by the George E. Brown, Jr. Near-Earth Object Survey Act of 2005 requiring NASA to identify ≥90% of potentially hazardous NEAs greater than 140 m in diameter. The catalog of >1 km NEAs is now >95% complete and there are good estimates of how many smaller bodies remain undiscovered [e.g., 6,7]. However, because >99% of the volume of NEAs is in objects ≥1 km in diameter (**Fig. 1**), we are able to ignore the smaller asteroids for this initial assessment.

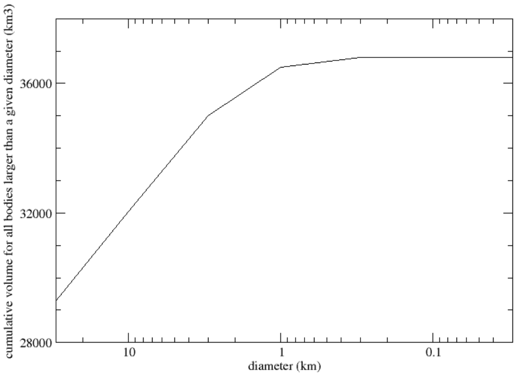

Figure 1. Cumulative volume of NEAs vs. diameter.

Tonnage Model: The fourth model describes the size distribution of deposits (i.e., asteroids). While there are some questions about the size distribution of the smaller bodies, the ≥1 km diameter objects are quite well characterized (**Fig. 1**). However, there are significant uncertainties in the mass represented by these bodies especially because the densities of asteroids are highly variable and difficult to estimate [8].

Grade Models: The final model in a USGS resource assessment describes the probability distribution of the quality (i.e., "grade") of the deposit. Resource quality is primarily governed by the concentration of the resource, but is also secondarily affected by how the resource is bound in the rock. For platinum, published reports have concentrations in metallic meteorites range from 0.5-30 ppm with an average of 11 ppm and around 8-9 ppm in the metallic phase of chondrites [9]. Native Fe-Ni alloys make up essentially all of metallic asteroids and as much as 25% of carbonaceous chondrites. The primary source of uncertainty is that only 5-20% of the asteroids in the X spectral group are actually metallic [10].

For water, we do not expect pure water ice to be found on NEAs in any meaningful concentration. Instead, we focus on hydrated minerals. While some primitive carbonaceous chondrites have >20 wt.% bound water, most have been heated sufficiently to contain a few percent water [11]. Furthermore, the concentration can vary significantly with depth if an asteroid has been heated for a geologically short time. There are also issues where the more primitive chondritic bodies are less likely to make it into the meteorite collection and the water content can be significantly altered during atmospheric entry and while the meteorite is on the Earth's surface.

Combining the Models to Create an Assessment: The final step is to combine the models in a statistically rigorous manner to obtain the total amount of each resource expected at the cumulative 10, 50, and 90% confidence levels. Because the statistical distributions in the locations, sizes, and compositions of ore bodies (and asteroids) do not fit simple statistical models, it has proven necessary to utilize Monte Carlo methods to do this combination correctly. For this step, we will use the same statistical software analysis package that the USGS uses for terrestrial mineral assessments that has been extensively validated and has all the capabilities we require.

Economics: To be economically viable, processed and delivered asteroid resources would need to cost less than having the same need supplied from Earth. For reference, the cost of platinum on Earth has been ~$30,000/kg in recent years. The cost of water and base metals is trivial on Earth, but transporting them to users in space is expensive. The ~$200 million Atlas V launch of MSL put just over 3000 kg on a transfer orbit to Mars, suggesting a cost in the ballpark of $50,000/kg for water (or anything else) to support a human crew traveling to Mars. It is worth emphasizing that the USGS does not assess the technologies or economics of resource extraction. Instead, the USGS assessment is the input data for others who examine those types of issues.

Next Steps: In order to complete the initial assessment of water, iron, and platinum in the NEA population we still need to complete the grade models, run the statistics, and compile a short written report, a draft of which should be complete near the time of LPSC 2016.

However, this initial report is fundamentally only a proof of concept and we recognize that significant additional work is required to complete an assessment that is truly useful for governments, businesses, and the general public.

For a more complete assessment, the top priority would be to remove several simplifying assumptions, especially related to estimating the composition of asteroids. The meteorite collection is a biased sample of the NEA population and there are steps that need to be taken to adjust for known issues. However, the "grade" models will never be robust without continued spectral observations of asteroids, especially in the infrared, to directly assess the distribution of different compositional classes of asteroids [7].

A complete assessment of "space resources" should also include other materials. Organics and bulk radiation shielding are examples of "minerals" that could be of broad interest. The assessment should also quantify the amount of each resource expected as a function of Δv since that may drive key decisions about the asteroid mining infrastructure that would be most economical. Assessments of the resources on the Moon and Mars are also needed to help choose future human exploration architectures to those bodies.

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