Space resources - What can we learn from centuries of exploration, mining, and assessment on Earth to better utilize the rest of the Solar System?, L.D. Meinert[1] and C.F. Williams[2], [1]USGS Scientist Emeritus, 128 F St. SE, Washington, DC 20003, LDmeinert@gmail.com, [2]Director USGS Geology, Minerals, Energy, and Geophysics Science Center, 345 Middlefield Road, MS 973, Menlo Park, CA 94025, colin@usgs.gov

Introduction: Mineral resources are the building blocks of civilization and have been used for millennia, in ever-increasing amounts, and with increasing diversity of critical elements. As human activity extends into space it will be necessary to source some of this material from extraterrestrial bodies (asteroids, moons, other planets) due to the prohibitive cost of transportation from Earth. Although the popular press envisions bringing space raw material back to Earth, this is unlikely because of the same issue with transportation costs. However, utilization of resources IN space is likely for propellent, infrastructure (housing, manufacturing facilities, transportation), and sustenance (food, water, air). It also is possible that certain space-manufactured goods (crystals, alloys, electronics) could be uniquely possible/valuable due to microgravity, vacuum, and chemical properties that are not possible on Earth.

Lessons learned from terrestrial exploration, mining, and assessment can be applied to space resources. This includes both emerging technologies such as geophysical, spectral, and microchemical techniques as well as more mundane measurements of rock/regolith density, porosity, strength, grindability, and thermal properties. Space resources are likely to be large relative to human needs and quantitatively assessing those resources for specific elements and localities is a necessary first step in their commercial development. No major mining company would undertake the huge cost of developing a new mine on Earth without a detailed resource model. Given the even higher costs of space travel and development, new space resource models and assessment techniques are a prerequisite for practical development of space resources. The present paper looks at how existing USGS methodologies and capabilities can be applied to the emerging field of space resources.

USGS Mission and Capabilities: The U.S. Geological Survey (USGS) has a mandate to assess mineral resources dating back to the founding Organic Act of 1879 (20 Stat. 394; 43 U.S.C. 31), which provided for "*the classification of the public lands and examination of the geological structure, mineral resources, and products…",* which was expanded in 1962 (76 Stat. 427; 43 U.S.C. 31(b)) to extend those examinations "outside the national domain."

In addition, the USGS has developed a significant partnership with NASA to expand its reach beyond the national domain, and indeed beyond the Earth itself including projects on 1) assessment of undiscovered, buried, and concealed mineral resources, 2) developing and using geophysical and remote sensing techniques to detect mineral occurrence, abundance, and composition in a wide range of target materials, 3) basic research on mineral properties and ore deposit genesis that can be used to predict occurrences in other countries, planets, and celestial bodies, and 4) specific projects to estimate the abundance and composition of asteroids and other extraterrestrial bodies to evaluate their potential as future mineral resources.

Resource Assessments: The standard USGS approach to quantitative mineral resource assessment utilizes a well-vetted three part methodology that incorporates known geological, geochemical, and geophysical information into identification of tracts that are evaluated for the possibility of various mineral resources based upon deposit models describing the characteristics of known deposits and ore systems [1] [2]. This results in a modeled number of deposits and contained metals at various statistical levels of certainty (typically 5%, mean, and 95% confidence levels). The general process is illustrated in Figure 1.

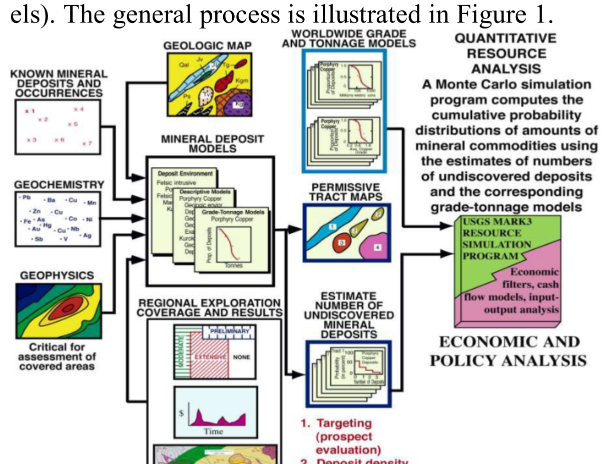

Figure 1. USGS three-part assessment methodology.

Such assessments have been done for particular geographic regions such as the State of Alaska, National Parks, and potential wilderness areas and for specified commodities such as the national assessment of gold, silver, copper, lead, and zinc in 1996 [3] and the global assessment for copper, platinum group elements (PGE), and potash in 2014 [4].

Space Resource Assessment: A feasibility study for the quantitative assessment of mineral resources in asteroids was published by the USGS in 2017 [5]. The descripitive model for this assessment was based on the petrology of meteorite classes found on Earth using the three main spectral categories (C, S, and X) of asteroids in the Small Main-belt Asteroid Spectroscopic Survey (SMASS) [6] and equating C asteroids with carbonaceous chondrites, X asteroids with iron meteorites and pallasites, and S asteroids with all other meteorites (which are mostly stony). This descriptive model was applied to near-Earth objects between the orbits of Earth and Mars, but excluding the main-belt asteroids. This descriptive model was then combined with the known composition of meteorites found on Earth and fed into a statistical Monte Carlo model called ASTRA1 that is described in more detail by [5]. This resulted in a 50% probability distribution of about 20,000 Gt of water and 100,000 Gt of metallic iron for the subset of asteroids studied as illustrated in Figure 2 and based on the assumptions described more fully in [5]. To put this in context, the only extraterrestrial human habitation to date, the International Space Station, has a mass of less than 400 tons and the crew of 6 uses about 5 tons of water per year.

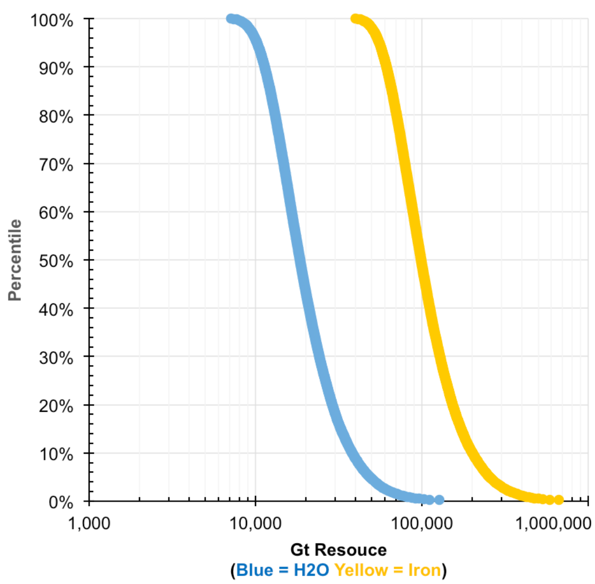

Figure 2 Output of ASTRA1 modeling showing how the minimum amount of water and metallic iron resources (in gigatons, Gt) in near-Earth objects would be represented in a USGS resource assessment.

This very preliminary feasibility study is a gross simplification but suffices to demonstrate the very large quantity of resources in space relative to the likely human need. To properly plan space exploration beyond the Earth-Moon system it will be necessary to have much better assessments of the resources available in space that can be utilized in place to support the transportation, housing, and sustenance of human beings. Such assessments will require a combination of remote sensing and physical sampling to better constrain actual asteroid, moon, and planetary compositions, at a scale appropriate for resource classification and potential utilization. This information can then be used to inform resource assessment models that have been developed and successfully utilized on Earth. Such model assessments will be foundational to guide policy and investment decisions concerning the emerging field of space resources.

References: [1] Singer, D.A. (1993) *Nonrenewable Resources, 2,* p. 69-81. [2] Singer, D.A., and Menzie, W.D. (2010) *Oxford University Press, New York,* 219 p. [3] Long, K.R., DeYoung, J.H., and Ludington, S. (2000) *Economic Geology 95,* p. 629-644. [4] Johnson, K.M., Hammarstrom, J.M., Zientek, M.L., and Dicken, C.L. (2014) *U.S. Geological Survey Fact Sheet, 2014–3004,* 3 p. [5] Keszthelyi, L., Hagerty, J., Bowers, A., Ellefsen, K., Ridley, I., King, T., Trilling, D., Moskovitz, N., and Grundy, W. (2017) *U.S. Geological Survey Open-File Report, 2017–1041,* 28 p. [6] Binzel R.P., Rivkin A.S., Stuart, J.S., Harris A.W., Bus S.J., and Burbine, T.H. (2004) *Icarus, v. 170,* p. 259–294.