SOLAR SYSTEM RESOURCE ASSESSMENT IN 2050. L. Keszthelyi[1], D. Trilling[2], J. Hagerty[1], N. Moskovitz[3] and M. Milazzo[1], [1]USGS Astrogeology Science Center, Flagstaff, AZ 86001, [2]Northern Arizona University, Flagstaff, AZ 86001, [3]Lowell Observatory, Flagstaff, AZ 86001.

Introduction: In 2015 the United States Geological Survey began a feasibility study for assessing natural resources in asteroids [1]. By 2050, we expect that such assessments will be a key "customer" of data collected by NASA planetary science missions. Here we (1) provide our rationale for expecting this need, (2) describe how such data would be used in USGS resource assessments, and (3) provide some specific mid-term activities that would lay the groundwork for robust resource assessments across the solar system in 2050.

Rationale for Solar System Resource Assessment: The long-term goal of the United States space program is establishing a human presence on Mars. This goal has been remarkably stable for decades, unfazed by changes in administration, geopolitical situations, economic conditions, and generations of the American public. One can debate the merit of this goal, but this core of our Nation's space policy can be expected to persist past 2050. Planetary science will thrive best if it is able to demonstrate its relevance to transforming humans into a true space-faring species.

Several major challenges must be overcome before there are human bootprints on Mars. The most problematic obstacle may be the price tag, a large fraction of which comes from hauling material out of Earth's gravity well. Obtaining key resources (e.g., water and metals) in the space between Earth and Mars could dramatically reduce the costs of a trip to Mars. A sustained human presence on Mars is only practical if local resources can be utilized. The most obvious way to obtain such resources is to mine near-Earth objects (NEOs) and the shallow subsurface of Mars (and perhaps the Moon). Enabling such mining will almost certainly be a key component of the US space program in 2050.

Before such mining can be prudently undertaken, unbiased, quantitative and reliable assessments of key resources will be needed. Creating such assessments is the Congressionally mandated responsibility of the United States Geological Survey. The "Organic Act" of 1879 established the USGS with a few specific obligations, including "the classification of public lands and examination of the geologic structure, mineral resources, and products…" In 1962, Congress extended those examinations to "beyond the borders of the United States."

In 2015, USGS management recognized that this phrase extends the USGS legal obligation to space. At this time Congress has not provided funding specifically to assess extra-terrestrial resources. Nevertheless, the USGS Mineral Resources Program decided that it was prudent to fund a small feasibility study to examine if existing terrestrial methods can be applied to asteroids. This effort has demonstrated that the USGS resource assessment methodology can be readily applied to asteroids. Furthermore, even this crude feasibility study is sufficient to robustly conclude that the NEO population could sustain at least a million-fold increase in the 2016 level of human activity in space for a million years – if the technology to extract the resources were to exist.

Given this potential to enable human activity in deep space, we expect that Congress will have directed the USGS by 2050 to provide resource assessments of the NEOs, likely landing sites on Mars, and perhaps the Moon. Before describing the kinds of data most desired for these future assessments, it is useful to briefly review the USGS methodology for resource assessments.

The USGS Resource Assessment Methodology: The USGS minerals, energy, and water resource assessments are all designed to produce unbiased and reliable results in a format readily understood by decision makers who are not technical experts in the field [2]. Here we adopt the terminology used in mineral assessments, but the concepts are similar for all resources. This methodology is often called the "three-part" model because it combines three separate quantitative models via numerical methods to produce the statistics for the final assessment.

For each resource, a prerequisite for quantitative assessments is the development of qualitative *descriptive models* of each geologic setting in which the resource can be found. This is a description of the association between the resource and geologic units and processes.

The first of the three quantitative models is the *spatial model*, which delineates tracts that contain the geologic setting described in the *descriptive model*. In other words, the *spatial model* is a map of the areas where the geology permits the existence of deposits of the resource, not a of map the resource deposits themselves [2]. The second model is the *grade-tonnage model* for each geologic setting. "Grade" is the concentration (or quality) of the resource and "tonnage" is mass (or quantity) of the deposit. These models are usually expressed mathematically as multivariate probability density functions (pdfs) for the resource concentrations and ore tonnages of the deposits in the assessment area. The third model is the *deposit-density model*, a mathematical description of the expected number of deposits per unit area.

The *deposit density* and *grade-tonnage models* are statistically combined to calculate the expected size and quality distribution of deposits per unit area at various confidence levels (typically 10, 50, and 90%). Monte Carlo methods are the most commonly used statistical method because of their flexibility and mathematical simplicity. An economic model that describes the cost to set up an extraction operation and then operate it can be applied. Even a simple parametric model is usually sufficient to indicate whether the expected deposits are worth extracting. After combining with the areas identified in the *spatial model*, the final outputs are (1) the minimum number, size, and quality of economically viable deposits at various confidence levels and (2) a map of where these deposits may exist.

It is worth re-iterating that this methodology can apply to any type of resource and decades of experience has shown that this is the most useful format to provide the assessment to decision makers.

Essential Preparatory Planetary Science Studies: Each of the models described above require deep scientific understanding and statistically meaningful volumes of data. Even though USGS has the legal mandate to conduct Solar System resource assessments, it will need to rely enormously on the efforts of NASA's Planetary Science Division to succeed. Based on our feasibility study, we can point to several efforts that are essential to enable useful resource assessments for NEOs, Mars, and beyond.

In-situ observations. First, to properly assess the grade of planetary resource deposits, we require many more detailed and systematic compositional measurements. The need is for more than bulk elemental and mineralogical information. The manner in which the resource is distributed, the mechanical properties of the host material and the types of trace contaminants can greatly affect how much of the desired resource can actually be extracted. For example, potable water would be easiest to extract from the shallow subsurface of Mars if it were in sizable layers of pure water-ice covered by loose regolith. Conversely, the water would be extremely difficult to utilize if it were predominantly bound to hydrated minerals in strong rocks and contaminated with toxic compounds such as perchlorates [3]. Similarly, metals would be easiest to extract from asteroids if they were in relatively small particles disseminated within a loose regolith with few embedded sulfides or silicates. Simply passing a magnet through such material could suffice. However, if the metal is in a massive piece, cutting off workable pieces in a microgravity environment will be a challenge. Even worse would be if the metal had to be broken out of hard rock and was laden with unwanted minerals that had to be chemically or physically removed.

To ascertain these types of properties, it is necessary to conduct in-situ studies supported with detailed laboratory investigation of returned samples. Furthermore, such studies would need to be conducted on a statistically meaningful number and variety of sites. It will be essential for the landed missions involved to be able to interact with the upper meters of the surface. While the drill on the InSight lander is one possible technological path, we suggest that penetrators may allow more cost-effective investigation of a large number of sites.

Linking in-situ to remote observations. No resource assessment can realistically rely solely on collection of in-situ data. Even on Earth, such studies are expensive enough to be available only sparsely. Instead, a deep understanding of the geologic processes that formed the deposit and its host materials is required to confidently extrapolate from the immediate vicinity of the in-situ measurements. The key is to link the geologic processes of interest to measurements that can be obtained on a regional scale via remote sensing. For example, the current linkage between spectra of asteroids and spectra of meteorite samples is not robust enough to direct asteroid mining missions to the best targets. The thermal and space-weathering processes that alter the outermost layers of an asteroid may hide key spectral features indicative of the real water content of an asteroid. With the aid of further in-situ investigation of asteroids and laboratory studies of meteorites, it may be possible to discover mineral assemblages indicative of high water content that have a spectral signature more robust to surficial alteration. It is likely that confidently identifying the desired geologic setting will require combining data from multiple different types of remote sensing observations.

Remote sensing observations. The ability to map out the locations with the right geologic setting to contain high abundances of high-grade resource deposits will almost certainly require combining data sets with very different spatial, temporal, and spectral characteristics. In many cases, including NEOs, there is a shortage of bodies that have been observed with the right combination of instruments, which is at least partially due to the fact that the bodies of greatest interest are very dark and the vast majority of them are small. Similarly, the regions of greatest interest on the Moon are poorly illuminated, limiting the types of remote sensing data that are available. Even as future instruments collect robust data from these challenging targets, it will be essential to develop the tools to properly fuse disparate data sets.

Conclusion. Assessing Solar System resources will be a major element of the US space program in 2050. A robust combination of in-situ and remote sensing observations are needed to enable those assessments.

References: [1] Keszthelyi L. et al (2016) LPSC Abstract #2254. [2] Singer D. A. (2007) *USGS Open-File Report 2007-1434*. [3] Hecht et al. (2009) *Sci.*, **325**, 64.