SOLAR SYSTEM RESOURCE ASSESSMENTS IN 2050

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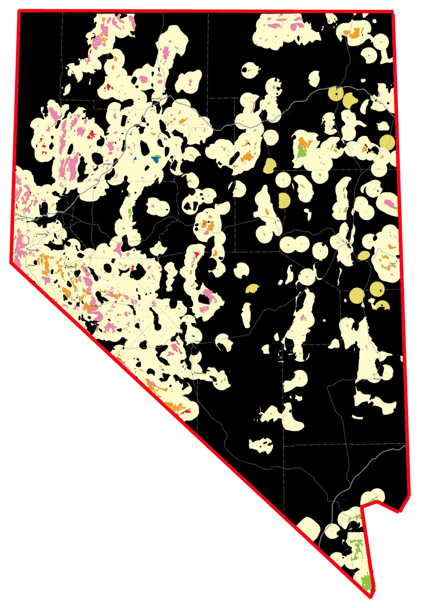
BACKGROUND: In 1879, Congress established the United States Geological Survey (USGS) primarily to provide assessments of the mineral and geologic resources within and beyond the borders of the Nation [1, 2]. Over the past several decades, the USGS has honed a methodology that provides private and government decision makers with reliable and unbiased quantitative assessments of resources across the Earth [3]. In November 2015 the "Spurring Private Aerospace Competitiveness and Entrepreneurship Act of 2015," was signed into law by the President, laying the legal foundation for US companies to extract resources in space. Not coincidentally, in October of 2015, the USGS Mineral Resources Program decided to fund a pilot study to extend these methods to asteroids. This study has been successfully completed and is in the process of final publication. Providing mineral and energy resource assessments is now essential for the USGS to meet its Congressionally-mandated core function in the 21st Century.

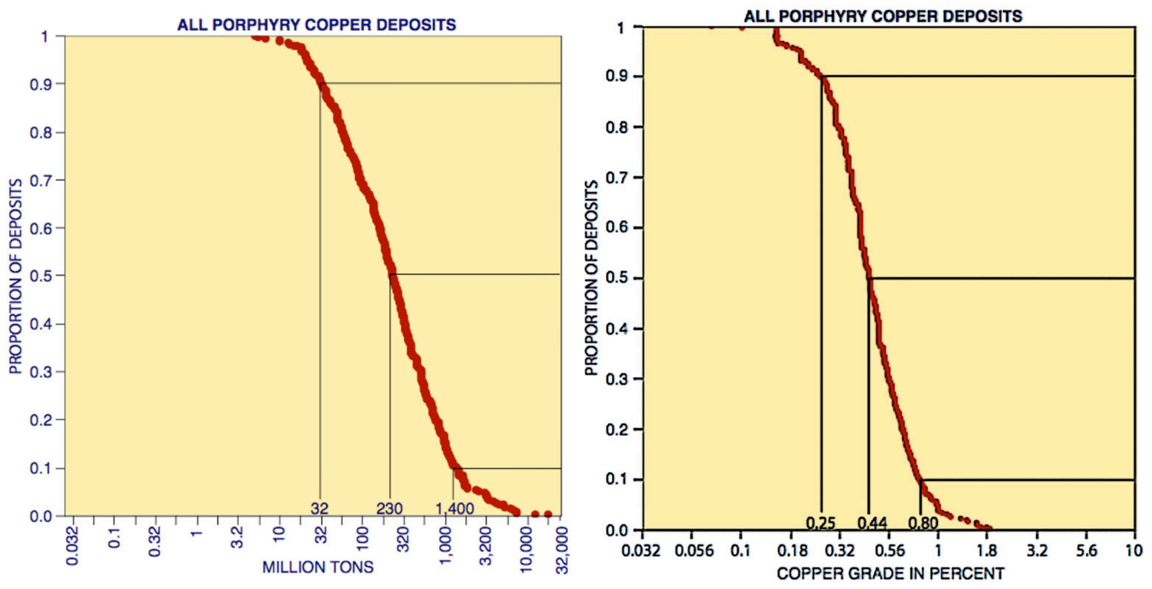
VISION FOR 2050: The USGS, in partnership with NASA, will provide the reliable, unbiased, accurate, and useful assessments of the mineral and energy resources across the Solar System needed to sustain the Nation's endeavors in space. This will be achieved by combining the USGS's nearly two centuries of experience providing such assessments on Earth with a century of experience working on Solar System bodies by government, educational, and private entities. These assessments will be the foundation of evidence-based science for critical decisions by mission designers, space policy makers, and private investors as humans establish themselves as species of space-faring explorers.

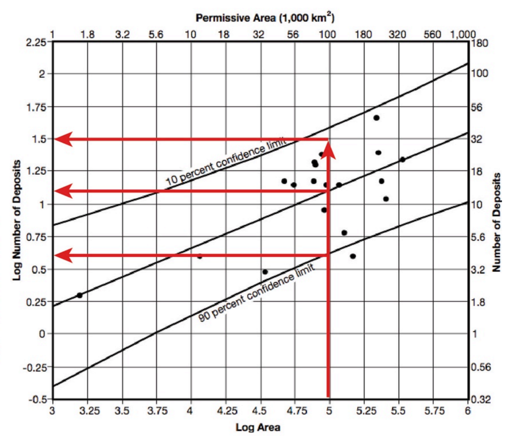
THE (TERRESTRIAL) USGS RESOURCE ASSESSMENT METHODOLOGY: The methodology used by the USGS has a qualitative model, three independent quantitative models, and an optional economic model that are combined via Monte Carlo methods to produce the statistics for the final assessment [4]. For each resource, a prerequisite is the development of qualitative *descriptive models* of each of the geologic setting in which the resource can be found. This is a conceptual model for how the resource is associated with geologic units and processes. To illustrate the method in action, we use a series of studies assessing porphyry copper deposits in the state of Nevada [5-7].

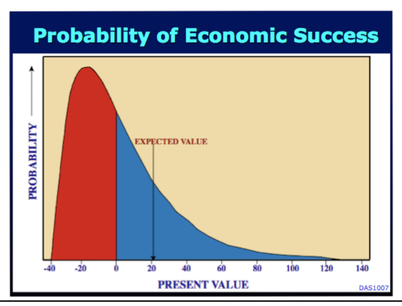


The first of the three quantitative models is the *spatial model*, which delineates tracts that contain the geologic setting described in the *descriptive model*. In the case of porphyry copper, these are locations where hydrothermal systems were set up around magmatic intrusions. The *spatial model* is a map of the areas where the geology permits the existence of deposits of the resource [3]. This is not an attempt to map the resource deposits themselves. The *spatial model* can exclude areas inaccessible due to technical, political or legal reasons. In the Nevada case, the state borders were a key constraint. Constructing a *spatial model* typically uses a wide variety of relevant data, including information on known deposits, geochemistry of samples, geophysical surveys, geologic mapping, and remote sensing. The spatial variability in the quality of the data is also considered. Combining all the different data is often requires automated classification methods (including neural nets, data fusion, and/or regression tree analysis). Map on the left shows the spatial model of Nevada where regional geology and geophysics permit porphyry copper deposits at the surface (pink and green) and shallow subsurface (yellow) [5].

The second quantitative model is the *grade-tonnage model*; "grade" is the concentration/quality of the resource and "tonnage" is mass/quantity of the deposit. The *grade-tonnage model* is summarized in two plots: (1) a size-frequency distribution and (2) a quality-frequency distribution of deposits in well-studied areas. The distributions are carefully fit with a statistical model to assure that the typically highly skewed distributions are properly represented. The panels on the right show *grade-tonnage models* for porphyry copper deposits [6]. The median deposits on Earth are 230 million tons with 0.44% Cu. However, note the small number (<10%) of very large and very high quality ore deposits that would fall outside a simplistic statistical fit to the typical deposits.

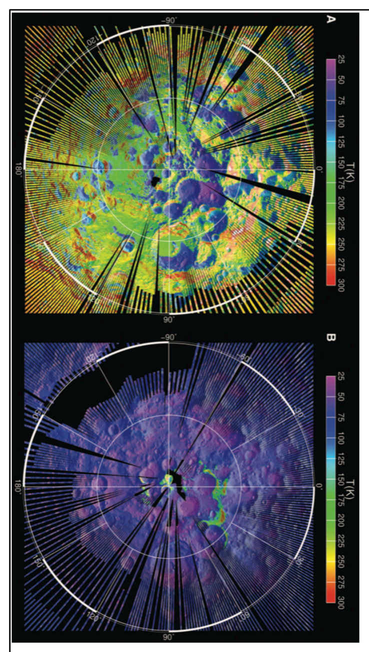






The third part is the *deposit-density model*, which describes the expected number of deposits per unit area. This is usually determined by examining a statistically meaningful number of localities in great detail to characterize all the deposits in those localities.

The *deposit density* and *grade-tonnage models* are combined using Monte Carlo methods to calculate the expected size and quality distribution of deposits per unit area at various confidence levels (typically 10, 50, and 90%). Then 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 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. In the Nevada case, 1 and 15 new deposits are expected at the 50, and 10% confidence levels [7]. In terms of return on investment, the most likely (i.e., modal) result is to lose money but the median result would be to make some money. This is difference is driven by the small chance of finding a very large and rich deposit. Note that these results say nothing about any individual mining venture but are useful at a higher level, e.g., giving the state of Nevada important input in deciding what incentives to provide the copper mining industry as a whole.



12 am/pm temperatures of the lunar south pole from DIVINER. From Paige et al. [2010b]

TRANSLATING THE USGS RESOURCE ASSESSMENT TERMINOLOGY: There are one-to-one translations between most of the concepts in terrestrial mineral resource assessments and studies of asteroids and associated meteorites. On Earth, the *descriptive model* records qualitative information about the geologic settings in which concentrations of the relevant resource can be found. For asteroids, this concept is equivalent to the major meteorite types defined on the basis of petrology, allowing us to consider three main types of deposits: stony, carbonaceous, and metal-rich. For the Moon, the geographic and physiographic location (e.g., permanently shadowed high-latitude crater floors) is as important as the hard-rock geology.

The *spatial model* describes where ore bodies can be found within boundaries set by political and technical limits. In space, each asteroid can be thought of as an ore body and spatial boundaries are best defined in terms of the energetic distance between objects (i.e., Δv). On the surface of the Moon or Mars, trafficability will be a major factor in setting the regions that can be considered for resource extraction. There are many parallels to the work behind landing site selection and certification that are familiar to planetary scientists.

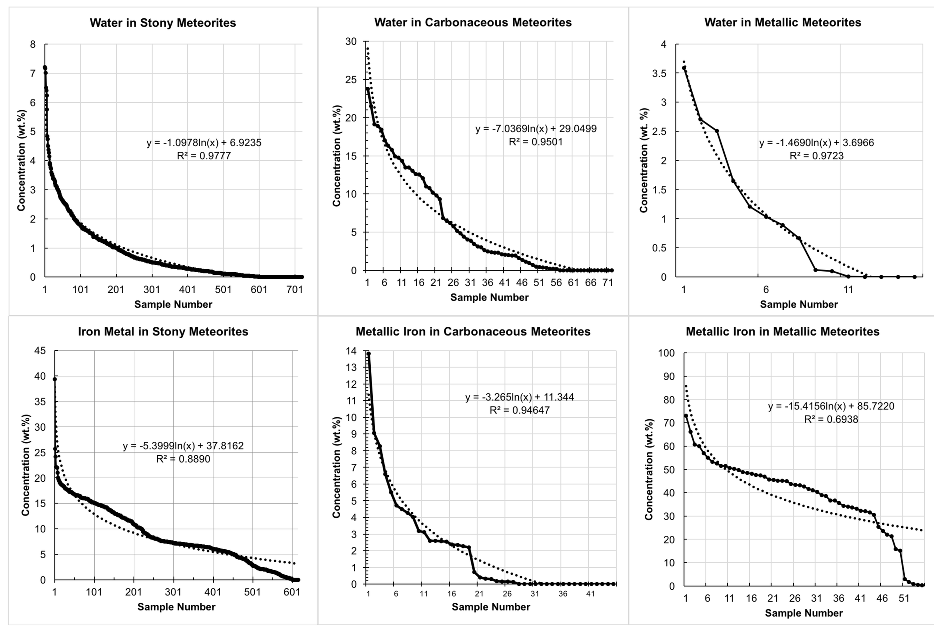
NEAR image of Eros, a large example of a typical near-Earth asteroid

SUCCESSFUL PILOT USGS ASSESSMENT OF NEO RESOURCES: As detailed in this panel, our pilot assessment was successful. Only superficial changes are required to the USGS mineral resource assessment methodology to make it applicable to asteroids. We also confirm that there is good reason to conduct a proper resource assessment of Near-Earth Objects (NEOs).

Compositional Group	Meteorite Classes from Nittler et al. (2004)
Stony	ACA, ANG, AUB, BENC, DIO, E, EH, EL, EUC, H, HOW, L, L/LL, LL, LOD, LUN, R SHE, URE
Carbonaceous	C, CI, CK, CM, CO, CR, CV
Metal-rich	IAB, IIE, MES, PALL

Assumed Meteorite Group	SMASS Spectral Type from Binzel et al. (2004)
Stony	A, K, K:, L, Ld, O, Q, R, S, S:, S(IV), Sa, Sk, Sl, Sq, Sq:, Sr, U, V, V:
Carbonaceous	B, C, C:, Cb, Cg, Ch, D, T
Metal-rich	X, X:, Xc, Xe, Xk,

Plots of fits to compositional data from Nittler et al. (2004) using the meteorite groupings in the tables above



It is not hard to translate terminology of terrestrial resource assessments into the language of planetary scientists. The *deposit density* model is the number density of NEOs. The *tonnage model* is the mass distribution of NEOs, derived from the brightness (absolute brightness) of the object and an estimate of its albedo and density. These parameters are almost exclusively obtained from telescopic observations that also serve to characterize NEO hazards.

The vast majority of the mass of NEOs is contained within the larger km-scale objects, so we consider only the 428 entries in the Minor Planets Catalog with M_H less than 18. The survey of these larger NEOs is considered 90-95% complete so we allow up to 43 additional undetected objects in our analyses. Albedo and density are well-constrained for only a few objects so we consider a reasonable range of values that vary for each spectral class. The resulting uncertainty in the mass of an individual object is of order "several."

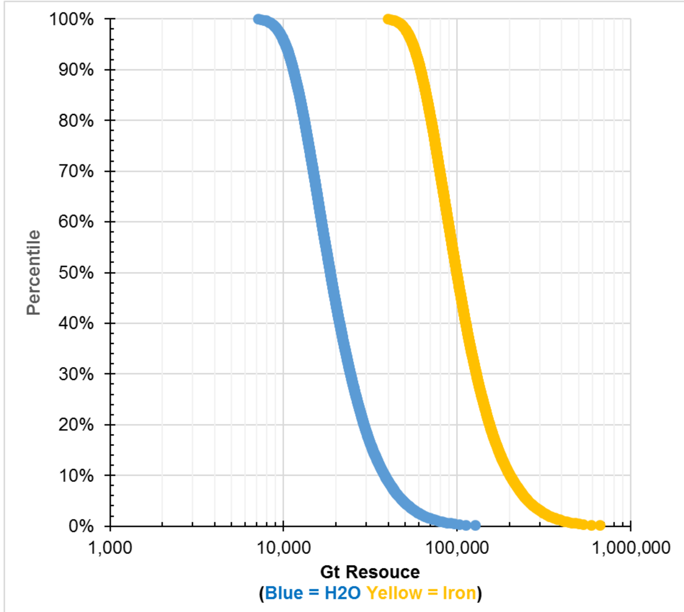
The *grade model* is the composition of the NEO. Detailed geochemical and petrologic data are available for almost all meteorites but is patchy (for example, few researchers measure the water content of iron meteorites). For our modeling, we fit curves to the data from Nittler et al. [10] as estimates of the probability distribution function for (bound) water and free Fe-Ni alloy but better data are desirable.

We can confidently link a meteorite to a specific NEO only in the rarest circumstances. Therefore the meteorite data are linked to NEOs by equating spectral classes to meteorite types. However, more high-quality infrared spectra of NEOs and spectra of meteorites under realistic conditions would both help. In particular, the effects of space weathering, temperature, vacuum, and grain size are important to include.

In a USGS resource assessment, amounts in the *grade model* are not simply multiplied with the *tonnage* and *deposit density models*. Instead, Monte Carlo methods are used to compute the statistics in a rigorous and robust way. While we do not use the best available data and have not included all the sources of uncertainty, it is clear that NEOs contain vast amounts of water and metal. In fact, if these resources were really usable, it would support a million-fold increase in the current human usage of water and metal in space for a million years. Even if this crude feasibility study is wrong by many orders of magnitude, NEO mineral deposits far exceed human space exploration needs for the foreseeable future.

	90% probability	50% probability	10% probability
Water	11,000 Gt	18,000 Gt	38,000 Gt
Iron metal	61,000 Gt	99,000 Gt	200,000 Gt

Results of 100,000 runs of the model illustrating the type of graphical and tabular results the assessment results in. Actual uncertainties are substantially larger than indicated in this simple feasibility study.



GETTING TO THE VISION BY 2050:
We can divide the hard work that needs to be done in the next 33 years into 3 categories: Science, Infrastructure, and Partnerships.

SCIENCE: As always, scientists want more data. In this case, there is a quantifiable reason to get that data – to reduce the uncertainties in the assessments. With lower uncertainties, it is possible to make meaningful statements about more specific questions. Instead of asking if there "is water on Mars," the question could be "how much potable water can we expect at a landing site in Gusev Crater and the ability to process material to a depth of 1.5 m." While all advances in our understanding of Solar System bodies will improve resource assessments, there are some data sets that are of special interest:

- Additional infrared spectra from asteroids
- Detailed measurements of volatiles and organics from asteroids.
- Detailed measurements of the contaminants in the ice on the Moon.
- Detailed measurements of how volatiles are distributed laterally and vertically in the lunar regolith.
- Identification of the sources and detailed chemistry of surface and near-surface water and ice on Mars.

INFRASTRUCTURE: The pilot study highlighted some key difficulties in conducting operational assessments using research data. For example, a systematic petrologic and compositional catalog of meteorites, using consistent methods, is needed. Similarly, there is a need for new spectral libraries to be built with measurements made in vacuum and appropriate temperatures. New systematic surveys of photometric and thermo-physical parameters are also needed. While the PDART program does support some of this kind of work, it would be appropriate for the USGS to play a larger role in these areas. Such efforts could build upon the spectral libraries and compositional/petrologic databases on rock samples for Earth that the USGS already maintains.

PARTNERSHIPS: USGS may have the official Congressional authority to conduct Solar System resource assessments, but it cannot do this work without close partnerships with NASA and researchers across academia, research institutes, and industry. One example of a long-lived partnership between NASA and USGS is the >40-year-old LANDSAT program. Or a more flexible model, where USGS contributes specific expertise and instruments focused on resource assessments to NASA planetary missions, may work better. The mechanisms for partnership with academia may be different than the traditional R&A grant process. By 2050 we can expect private commercial ventures to be well-underway prospecting asteroids and the Moon. These assessments need to support all these endeavors evenly which introduces manageable but significant ethics issues. Of course, none of this will happen without good communication and working relationships with Congress. Building up and maintaining this network of institutions and interests will likely to be the biggest challenge on the way to achieving the vision by 2050.

REFERENCES:

[1] 20 Stat. 394; 43 U.S.C. 31
[2] 76 Stat. 427; 43 U.S.C. 31(b)
[3] Singer, D. A. (2007) USGS Open-File Report 2007-1434, 13 pp.
[4] Abell, P. et al. (2015) AAS DPS Meeting 47, Abstract 312.06
[5] Cox, D. et al. (1996) Nevada Bureau of Mines and Geology Open-File Report 92-2, p. 12-1 – 12-25.
[6] Singer et al. (2008) USGS Open-File Report 2008-1155, 45 pp.
[7] Singer, D. A. and W. D. Menzie (2010) Quantitative Mineral Resource Assessment, Oxford Univ. Press, 219 pp.
[8] http://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html
[9] Binzel, R. P. et al. (2004) Icarus, 170, 259-294.
[10] Nittler, L. R. et al. (2004) Antarct. Meteorite Res., 17, 233-253.
[11] https://www.nasa.gov/feature/apis-asteroid-provided-in-situ-supplies-100mt-of-water-from-a-single-falcon-9