Some Strategic Considerations Related to the Potential Use of Water Resource Deposits on Mars by Future Human Explorers

D.W. Beaty[1], R.P. Mueller[2], D.B. Bussey[3], R.M. Davis[3], L.E. Hays[1], and S.J. Hoffman[4], and E. Zbinden[5]

[1] Mars Program Office, Jet Propulsion Laboratory, California Institute of Technology 4800 Oak Grove Dr, Pasadena, CA 91109; email: david.w.beaty@jpl.nasa.gov, lindsay.e.hays@jpl.nasa.gov; [2] NASA Kennedy Space Center, Swamp Works, Mail Stop: UB-R1, KSC, FL 32899; email: rob.mueller@nasa.gov; [3] Planetary Science Division, NASA Headquarters 300 E St. SW Washington, DC 20037; email: david.b.bussey@nasa.gov, richard.m.davis@nasa.gov; [4] Science Applications International Corporation, NASA Johnson Space Center, 2450 NASA Parkway, Houston TX 77058; email: stephen.j.hoffman@nasa.gov, [5] Geological Society of Nevada, E_Zbinden@geology.reno.nv.us.

ABSTRACT

A long-term base on Mars, at the center of an "Exploration Zone", would require substantial quantities of in-situ resources. Although water is not the only resource on Mars of potential interest, it stands out as the one that most dominates long-lead strategic planning. It is needed for multiple aspects of various human activities (including our own survival), and in significant quantities. The absence of a viable deposits could make a surface "field station" logistically unsustainable. Therefore, identification of deposits, and development of the technology needed to make use of these deposits, are an important priority in the period leading up to a human mission to Mars. Given our present understanding of Mars, ice and hydrated minerals appear to be the best potential sources for the quantity of water expected to be needed. The methods for their extraction would be different for these two classes of deposits, and at the present time it is unknown which would ultimately be an optimal solution. The deposits themselves would ultimately have to be judged by an economic assessment that takes into account information about geologic and engineering attributes and the "cost" of obtaining this information. Ultimately, much of this information would need to come from precursor missions, which would be essential if utilization of martian is situ water resources is to become a part of human exploration of Mars.

INTRODUCTION

As a part of its Evolvable Mars Campaign (Goodliff et al., 2015), NASA is investigating options for making the human exploration of Mars both affordable and sustainable in a pioneering context. The Evolvable Mars Campaign is an ongoing study identifying potential options that could lead to sustainable human exploration of Mars. This campaign would leverage existing activities, and adapt to capability developments, scientific discovery, and ever-changing programmatic environments.

The results of this analysis will develop potential human Mars exploration strategies to inform NASA management on key decision options and investment priorities (Craig et al., 2015). A core concept is to establish a permanent presence at a long-term base. Such a base would be at the center of an "Exploration Zone" where significant and diverse science research could be conducted (see HSO-SAG, 2015; http://www.hou.usra.edu/meetings/explorationzone2015/). This kind of base would allow for equipment, infrastructure, and supplies to be built up over time, thereby providing progressively more capablities for the human explorers. If, in an analogy is the McMurdo Base in Antarctica, the base is long-lived, and could not be easily moved due to infrastructure, its near-term and long-term natural resource requirements need to be considered in the siting of the base. The purpose of this report is to evaluate some of the strategic considerations associated with planning for the availability of viable resource deposits on Mars.

On Earth, human civilization is dependent on a number of natural resources that are valued in approximate proportion to their relative abundance (or scarcity), ease of access, and usefulness. These include things like water, arable soil, timber, metals, and petroleum, natural gas, and coal. In order to achieve a sustainable and affordable human presence on Mars, it will almost certainly be necessary to break the logistical supply chain from Earth for at least some commodities. This is especially true for commodities that are required in high volume or are particularly massive, which would complicate spacecraft transportation operations. Safe delivery of large masses to the martian surface is uniquely difficult and expensive. This leads to crucial trades between finding and developing resources on Mars vs. simply delivering resources that were acquired elsewhere (see e.g. Drake et al. 2009, and references therein).

THE SIGNIFICANCE OF WATER AS A LOCATION-DEPENDENT MARTIAN RESOURCE

Importantly, because of differences in both the availability of different kinds of resources on Mars, and the priorities of the future human customers for local sources of supply, some key aspects of resource planning for Mars are rather dissimilar to that on the Earth. The martian atmosphere contains certain components of interest, and the ISRU community has justifiably paid close attention to it. However, the atmosphere is well-mixed, and is present everywhere on the martian surface, so it plays no role in site selection. Certain metals (e.g. Cu, Fe, Al, etc.) are very important to engineering, but we do not yet know if they have been concentrated into "ore deposits" on Mars by any natural martian processes. It may, of course, be possible to extract metallic commodities from "average" rock/regolith (a process that is extraordinarily energy intensive), but again, that would have no effect on site selection.

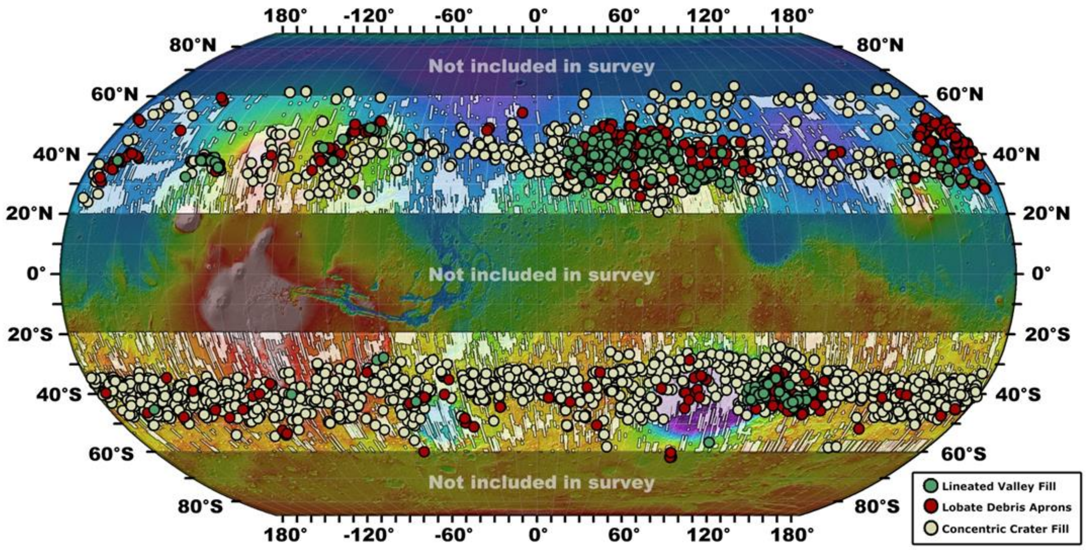
In planning for the eventual human exploration of Mars, we have become increasingly aware of the crucial role of water as a central commodity (Christensen, 2006; Sanders, 2010; Beaty et al., 2012). We know that water would be needed for multiple purposes, including the direct needs of the human crew, but also to provide radiation shielding, to cool EVA suits, to generate food, and potentially to make propellants for use in surface transportation vehicles and launch vehicles to return crews to waiting space transportation vehicles in Mars orbit. In addition, water is essential for its use in many manufacturing and industrial processes, for which the specific requirements on Mars will evolve in the future. The importance of water as a resource is heightened by the NASAs focus on creating a sustainable long term presence on Mars through the creation of a semi-permanent base to be visited by multiple crews.

We submit that identification of water resource deposits, as well as the technology developments to mine, beneficiate and extract them, need to be a priority in the period leading up to establishment of the first sustainable human base. As is the case in all planning related to ore deposits, location is everything, and this MUST be considered in advance of selection of the site of a potential human base. Although other types of resource deposits (e.g. certain metals, industrial commodities) may become important later, a crucial initial and on-going advantage for establishing a base for extended human crew habitation would revolve around the presence of accessible water.

CATEGORIES OF MARTIAN WATER DEPOSITS WITH POTENTIAL TO SUPPORT A HUMAN BASE

Although Mars has the potential for several categories of natural water resource deposits, only two are currently believed to be capable of generating water in the quantity and rate necessary to be practical, given current concepts for sustained human presence on the martian surface (for a recent summary, see MEPAG SR2-SAG, 2014, and references therein).

1) Ice occurs on Mars in different forms, depending on latitude: surficial polar caps at high-latitudes, continuous shallow permafrost at lower latitudes, and discontinuous, more deeply buried (more than a meter but possibly within 15m of the surface) ground ice within the mid-latitudes. In different places, this ice can be directly observed today, can be detected using geophysics, and/or can be inferred through geomorphic evidence. Of particular importance, Mars is currently emerging from a glacial maximum that pushed ice equatorward as far as 30º latitude (see Fig. 1). Because present understanding of the design of the surface system implies a site equatorward of ~50º latitude, the remnant glacial ice between 30-50º N and S constitutes a potentially important target.
2) Hydrated minerals and glass are found in the rocks and regolith in some places at the martian surface (see Feldman et al. 2004 for generalities; Ehlmann and Edwards, 2014, and Vaniman et al. 2014 for details). Various hydrated minerals have been detected, including several phyllosilicates, hydrated sulfate salts (including gypsum), hydrated iron oxides, amphibole, and others, which individually may contain water contents up to ~35%, though are often closer to ~15%. Glass and amorphous materials (Ming et al. 2014) also contain water. All of these materials will release water when heated—this is potentially the basis for a water recovery system. However, the concentration of the various hydrated components is both highly heterogeneous and poorly constrained.



<u>Figure 1.</u> Map of three major geomorphic features interpreted to have formed by glacial processes (from Dickson et al., 2012). For the purpose of resource exploration, this is a map of ice "potential". These features are relatively abundant between about 30-60ºN and 30-60ºS latitude. Although these occurrences are interpreted to have had a formative relationship to ice, in most cases we have no information about whether ice remains today in the shallow subsurface, and if so, at what depth and concentration.

For the purpose of this paper, three other candidate sources of water are considered impractical, and are not discussed further.

- <u>Deep groundwater</u>: Although water probably exists in the deep martian subsurface (e.g. Clifford et al. 2010), long-running radar surveys (MARSIS, SHARAD) have been unable to detect a water table anywhere on the planet, and the data are considered relatively definitive down to depths of ~200-300 m (see Rummel et al., 2014). The actual depth to a water table could be an order of magnitude deeper than this. There is significant uncertainty as to whether this resource exists in a place that is accessible by human engineering.
- <u>Water from the atmosphere.</u> The martian atmosphere contains a small amount of water. However, the partial pressure is so low (measured in precipitatable microns, the equivalent depth if all the vapor were condensed) that recovery at the rates needed to support a human mission is impractical.
- <u>High-latitude ice.</u> Although martian ice deposits poleward of ~60° have enough continuity and predictability that they can reasonably be assumed to be present with minimal or no exploration (Levrard et al. 2004, Mellon et al. 2009), there are severe operational (e.g. propellant consumed during launch and landing) and environmental (e.g. meters thick layers of CO_2 ice form in the winter) consequences to operating a landed mission at such high latitudes, and current assessments are that these would be impractical for a human mission.

- A note about RSL deposits. It has recently been announced that features referred to as “Recurring Slope Lineae” (RSL) may contain some amount of saline water on steep slopes during some portions of the year (Ojha et al. 2015). It is as yet unclear if the RSL features have the right combination of ease of access and concentration of water to justify a recovery operation—further evaluation of this option is deferred to future researchers.

A TALE OF TWO PATHWAYS

Although we have some experience mining both of ice and hydrated mineral deposits on Earth for commercial purposes (the mining of lake ice for refrigeration purposes during the past century, and the bulk mining of gypsum for the manufacture of sheet rock), we have no meaningful experience extracting and collecting the water present in these resources. If these two general kinds of potential water resource deposits on Mars were developed using traditional terrestrial mining methods, there are some obvious differences:

  - The mining system for an ice-based deposit may require higher excavation forces—ice-cemented regolith, for example, can be mechanically very tough. Granular deposits of minerals, such as in a sand dune, are potentially far more tractable.
  - The grade of water-bearing mineral deposits (typically 1-3% based on RAD data from MSL (Mitrofanov et al. 2014), but locally as high as ~10%) would be significantly lower than that of ice deposits, which could be nearly as high as 100%. This would mean that far more mass would need to be moved, and heated, for the mineral scenario. However, this would be partially offset by the fact that the stripping ratio is almost certain to be more favorable for the mineral deposits.
  - For mineral feedstock, the water recovery plant would need to operate at higher temperature (to reach mineral decomposition temperatures of typically 100s of degrees Celsius, as opposed to the temperature needed to melt ice)—this would require more energy.
  - There is likely to be a difference in the quality of the water produced from these two classes of deposits, but refinement may be required in both cases.

It is quite unclear how these kinds of trade-offs would translate to an optimized solution involving both the geology and the engineering. At some point in the future we will have enough information to be able to down-select between these two options, but we are not there now, so both technology thrusts should be advanced. That ultimate down-selection decision will need to be based on three critical factors:

- The “quality/quantity” of the respective deposits. This information would need to come from robotic martian exploration.
- The comparative attributes of the engineering systems. This information would need to come from the technology development programs and extensive testing in relevant environments.
- Implications of these two pathways on the rest of the mission. For example, accessible deposits of ice are not believed to exist within the equatorial belt, and

human landing sites outside of this equatorial band may have significant associated thermal, flight dynamics, and other kinds of issues.

HOW TO ESTABLISH RESOURCES: THE EXPLORATION PROCESS

All resource exploration begins with the recognition of potential. At the beginning, this potential is a wonderful thing—it typically represents the best a place or region could be, with any questions answered in the most positive way. However, we have to be careful not to let potential be confused with reality. Exploration projects will never look as good in their life-cycle as when they are at the potential stage—the acquisition of data almost always exposes realities that are less than ideal. An interesting aspect of resource potential is that it commonly can be contoured, with specific places having relatively high or relatively low potential of ore existence.

THE EXPLORATION-PRODUCTION LIFE CYCLE

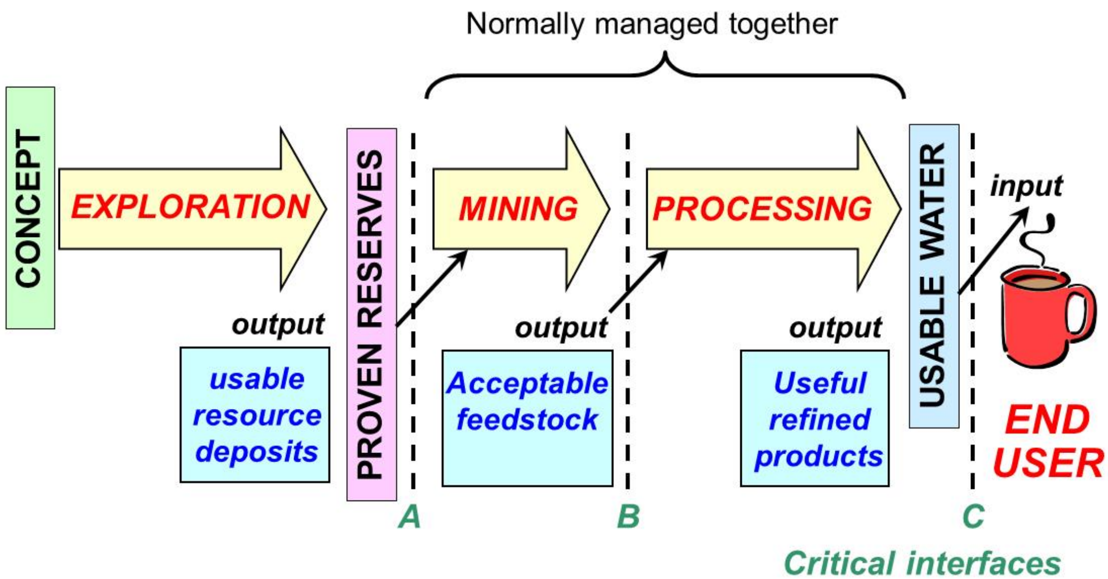


Figure 2. The basic flow to deliver resource-derived products that are acceptable to an end user has three primary phases, each defined by a supplier-customer relationship. Proper management of the interfaces (A-C) between these phases is a prerequisite for success.

Figure 2 illustrates the basic work flow which would result in the delivery of products originating from natural resources that are deemed useful by the end user. This flow is general enough that it encompasses many lessons learned "the hard way" here on Earth, and that can be confidently applied to Mars. There are three phases, which can be thought of as comprising the overall effort: Exploration, Mining, and Processing. Each phase is defined by a broad set of activities that result in a specific output. The output of each phase constitutes the input to the next phase. This flow defines three primary interfaces, which are characterized by supplier-receiver relationships. A key point is that the acceptability of the output/input is always determined by the receiver, as the receiver always has certain minimum standards of quality (e.g. concentration, state, nature of impurities, etc.) that need to be satisfied in order for their system to function. At a higher level, the entire operation needs to be able to deliver the quantity, quality, location, rate, etc. that is required by the end-user. If any of the above is insufficient in some way, the end-user does not get what he/she requires, and the overall system would be deemed unacceptable.

A CRITICAL CHICKEN-EGG ISSUE

One of the crucial lessons learned from the many historical successes and failures in the resource industry on Earth is that there is a chicken and egg relationship between "science" (exploration) and "engineering" (production). In order to delineate ore deposits that are usable in a practical sense, knowledge of the production/extraction system is needed. In order to design an effective production/extraction system, knowledge of the ore deposits is needed. On Earth, the two sides of this problem have "grown up" together over the course of human history, but for Mars we would need to advance both science and engineering together from a highly immature state. An unproductive outcome would be that the exploration process generates impractical resource deposits that are of interest only to academics, or a production system that is developed for which no suitable ore deposit can be discovered. Having an effective interface between the exploration and production/processing sides of Fig. 2 (Interface A) is essential to success.

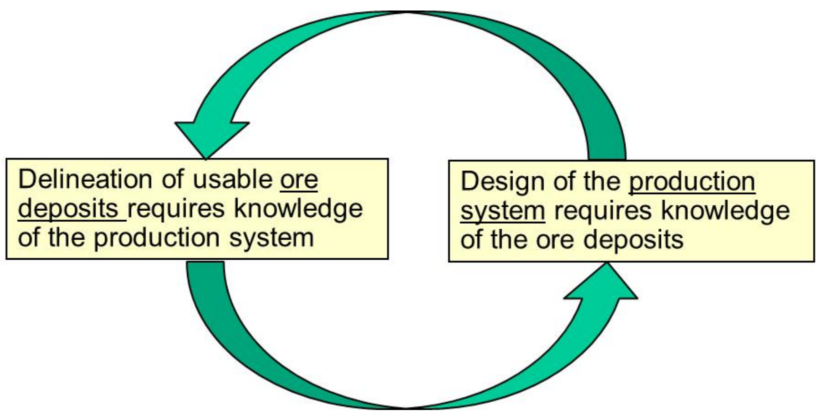


Figure 3. The chicken-egg relationship between exploration and production for natural resource deposits—these two things need to advance together.

CONFIDENCE: THE CONCEPT OF RESERVES

To determine whether the potential of a prospect is realized or not requires evaluation using scientific methods. As discussed above (Fig. 3), this in turn requires specification of the means by which the deposit would be produced and converted into a useful (and on Earth, economically viable) product. For example, the minimum required attributes of a gold deposit to be mined using open pit methods and extracted using heap-leach technology, are different from those of a gold deposit to be mined using underground methods and extracted using a mill.

One of the fundamental tenets of resource exploration is that there is no such thing as perfect or complete information. In natural resource exploration, we always face the question of how much uncertainty can be accepted. There is a threshold above which the information is deemed sufficient to make decisions with acceptable confidence, and the goal is to get to that threshold. The confidence with which a resource deposit is known to be present, and in a position and configuration that is minable with a viable technology, is embodied in the concept of "reserves". The term "reserve" can be defined to mean that a volume of material that is minable or processable, has been shown to exist, and to within a certain standard of proof. Reserves are graded from possible to probable to proven, depending on the confidence level. Here on Earth, the practical definition of proven reserves is that it is possible to use them as collateral to take out a bank loan (and loan officers are traditionally very conservative). For Mars, we could perhaps use the parallel definition that "proven" means we are willing to bet the lives of a crew of astronauts that the deposit is there in the quantity, quality, and form stated.

On Mars, the concept of reserves implies that the mining and processing systems are expected to be able to extract the water and to deliver it to the end user, with acceptable "cost". On Earth, that cost is defined by our economic system, and it is certain that on Mars, some cost-like factors (e.g. energy, time, effort) would be of central importance. For Mars, we don't know yet how the distinction between deposits that are judged to be sufficient and insufficient will be drawn, but many of the same component technical factors as used on Earth would likely be relevant. These factors would originate in both geological attributes (grade, size, mineralogy, etc.) AND physical or engineering attributes (e.g. depth, distance, topography to be traversed, etc.). A crucial point is that these factors can be traded off against each other, and that evaluations of individual factors in isolation would almost certainly not be meaningful.

Ascending the scale possible → probable → proven requires information, and in many different categories. Things that are unknown add risk, which reduces confidence. The information needs of hydrated minerals and subsurface ice would be similar in some key respects, but dissimilar in others.

- Since the valuable component is different (ice vs. hydrated minerals), different kinds of instruments are needed to detect the presence and quantity of these two components.
- The mining systems would mostly require similar kinds of information, related to "orebody" configuration, stripping ratio, and the mechanical properties of the rock to be excavated/moved.
- Planning for the extraction of water from delivered ore would likely require information about the concentration and form of the water-bearing species, and in both cases, the water would be recovered by heating (although the specific energy would be very different in the two cases).
- In order to plan for the above, the quality of the water to be delivered to the end user needs to be specified, and this of course depends on how the water would be used. For example, the water to be used in the

manufacture of rocket fuel may have different quality requirements than the water to be used for direct human consumption, or for growing food.

A summary of the kinds of parameters that may be required to make a credible claim of "proven reserves" of a water ore deposit on Mars is shown in Figure 4. The minimum acceptable values for these various parameters have not been established (represented by the many "TBD"s on the figure). In fact, since it is quite clear that there would be important trade-offs between these parameters, it may be that specific values would be hard to construct for some of them. Two key aspects of Figure 4 are:

- Not all of the types of knowledge listed are equally valuable (and this applies to resource exploration on both Earth and Mars). Our Earth experience is that the decisions on which types of information to acquire can be one of the most important factors that determines the success or failure of an exploration project. Exploration is cost-constrained (also true of both Earth and Mars), and we cannot afford to buy all of the information we want. Thus, prioritization is essential. Importantly, information acquisition decisions are typically needed relatively early in the exploration life cycle—especially true of Mars because of the long lead time associated with planning for spacecraft missions.
- Understanding the trade-offs between parameters is essential, since it will be impossible to find a deposit that simultaneously optimizes all of the parameters on Figure 4. For example, is a deposit of higher concentration that has a higher stripping ratio better or worse than a deposit that is of lower concentration but a lower stripping ratio? In order to understand these various trades, the potential benefit or impact of each of the various elements on Figure 4 need to be evaluated.

	Minimum Spec.	
Things that we would like to know	**Mineral**	**Ice**
• Depth to top of deposit (stripping ratio), geometry, size	TBD	TBD
• Concentration (and its variability) and state of water within the minable volume	TBD	TBD
• Geotechnical properties – large-scale properties ("minability"), e.g. competence, hardness – fine-scale properties ("processability") , e.g. competence, mineralogy	TBD	TBD
• The nature and scale of heterogeneity	TBD	TBD
• Location relative to power source and processing plant	TBD	TBD
• Amenability of the terrain for transportation	TBD	TBD
• Presence/absence of deleterious impurities	TBD	TBD

Figure 4. Unprioritized examples of information that may be needed to get to "reserves". The two columns on the right represent the minimum acceptable specifications for mineral- and ice-based resource deposits. Note that the

different categories of information are neither of equal priority nor of equal cost to acquire. (TBD = To Be Determined)

A special note: One of the endearing or terrifying aspects of geology (depending on your perspective!) is that geologic deposits are heterogeneous—that is to say that their properties are typically not constant across a given volume. We have to expect that martian water resource deposits, of either category discussed in this paper, will also be so. The open question is the spatial scale, character, and magnitude of that heterogeneity. If the viability of martian resource deposit and its coupled engineering system is dependent on a certain degree of homogeneity, it would be prudent to establish what this degree is before making major commitments.

THE NEED FOR PRE-HUMAN ROBOTIC EXPLORATION MISSIONS AND TECHNOLOGY DEVELOPMENT

For all classes of water resource deposits between about 50ºN and 50ºS latitude (one version of the acceptable latitude limits for a human field station), our present reality is near the left side of the flow chart on Fig. 2 – closer to the "concept" stage than the "reserve" stage. It is clear that in order to get to the first critical interface (Interface A--the establishment of proven reserves), a substantial amount of exploration work is required.

MEPAG P-SAG (2012) flagged the search for the water deposits needed for In-Situ Resource Utilization (ISRU) as the highest-priority precursor activity required to prepare for sustained human presence on Mars. They concluded that the technical need would require at least one properly equipped orbiter, and one additional mission to the surface. A resource exploration program could perhaps be thought of as consisting of the following phases:

- A phase where orbital data needs to be improved. Some of those improvement characteristics likely include: Improved areal coverage by the HiRISE, CRISM, and SHARAD instruments on MRO, and better spatial resolution and subsurface imaging by a future orbiter. These data need to be sufficient to a) identify prospects, and b) prioritize those prospects.
- A phase of technology development here on Earth where the real constraints on accessing and processing raw material on Mars are better understood. This could, and should, be done concurrently with the activity of the first bullet.
- A transition point, where we have learned as much as we can (or need to) from orbit and landed exploration assets would need to be brought to bear.
- A phase of ground-based exploration to prove ISRU water reserves, sent to one or more of the high-priority prospects identified in the above process. It is challenging to be specific about the needs of such a mission this far in advance, but it is hard to imagine how this could be done without mobility, some sort of test excavation and sample analysis capability, and subsurface geophysical sensors. Multi-sample capability is needed to give enough spatial coverage to begin to address the variability of all the important deposit parameters.

Note that there would certainly be overlap between ISRU-desired/required data and data of interest for reasons related to scientific questions. Both orbital and landed missions could certainly be credibly represented as having dual purpose.

An important MEPAG committee (NEX-SAG, 2015) was recently tasked with developing concepts for such a future orbiter. In their vision of this orbiter, one of the four goals would be to find water resources on Mars in support of potential future human surface exploration. Two specific proposed objectives for this orbiter are:

A. Find and quantify the extent of shallow ground ice within a few meters of the surface and characterize its ice-free overburden.
B. Identify deposits with hydrated minerals as a water resource, and potential contaminants within these deposits.

CONCLUSIONS

Natural deposits on Mars capable of producing significant amounts of water are strategically important. Defining "proven reserves" for such a deposit, which would provide the needed information for that interface between science and engineering ISRU concerns (Figure 2), would require:

1) A carefully designed exploration program consisting of both orbital and landed surveys. Information of sufficient fidelity cannot be obtained without both types.
2) Development of robotic mining, beneficiation and water extraction systems that are capable of acquiring and processing reserves defined in #1 above, and that are amenable to spaceflight, and operation under martian conditions.
3) An understanding of the trade-offs, to both geology and to engineering, of dealing with ore deposits on Mars that are less than ideal in every respect.

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