PROSPECTING FOR LUNAR AND MARTIAN RESOURCES. G. Jeffrey Taylor and Linda Martel (Hawai`i Institute of Geophysics and Planetology, University of Hawai`i, 2525 Correa Rd., Honolulu, HI 96822; gjtaylor@higp.hawaii.edu).

Space resources are essential for space settlement: Large space settlements on the Moon or Mars (more than a few thousand people) will require use of indigenous resources to build and maintain the infrastructure and generate products for export. Prospecting for these resources on the Moon and Mars is a crucial step in human migration to space and needs to begin before settlement and the establishment of industrial complexes.

A Plan of Action: We are devising a multi-faceted approach to prospect for resources that involves planetary research, technology development, human workforce development, and education. First, we need to develop a strategy and methodology for resource exploration on the Moon and Mars. This will include theoretical considerations for resource exploration, based on terrestrial experience and knowledge of the geology of the Moon and Mars. It also entails examining the full range of exploration techniques (orbiters, airplanes, balloons, rovers, teleoperated rovers, and humans), including types of instruments needed. We must also make a preliminary search and inventory of the resources of the Moon and Mars using existing and soon-to-be-acquired data (e.g. 2001 Mars Odyssey). Second, we must begin to train the workforce who will be the planetary economic geologists of the future. Student participation can range from graduate training in planetary economic geology to undergraduate coursework in planetary ore deposits and economic geology to precollege activities about the fascination and realization of extraterrestrial prospecting for self-sufficient settlements.

Developing the methodology for planetary prospecting: Work should focus on the unusual economics of planetary ores, including the relationship of lunar and Martian development to each other. As part of the assessment of potential planetary ore deposits, we will need to develop a new classification of ore deposits in a planetary context. This will guide us in our search for ore deposits on the Moon and Mars.

Economics of planetary ore deposits. We will develop models that define what ore deposits are on other planets. By definition (1), ores are "rocks or minerals that can be mined, processed, and delivered to the marketplace or to technology at a profit." The planetary context tosses in some interesting twists to this definition. First, the costs are compared to getting materials or products from the Earth or another planetary body, a very different case than for terrestrial ores to be used on Earth. Second, we must consider the cost of delivering extraction equipment to the Moon or Mars; these costs are much higher than delivering mining equipment to a location on Earth. The cost of extraction equipment becomes less important as a settlement grows, eventually becoming moot when local planetary industry can manufacture all equipment needed. For example, the cost effectiveness of some Martian resources (e.g., water, oxygen, hydrogen, major metals, and food) will have to be judged against their production on the Moon and shipment to Mars, which may be particularly pertinent during the early phases of Martian settlement. As we begin to settle the Moon and Mars, we must also keep track of changing economic conditions, such as launch costs or substitutes of one material for another.

Theoretical Assessment of Potential Ore Deposits. A basic framework for understanding how ores form and in what geologic settings they occur guides the search for ore deposits on Earth. This will form the basis of our theoretical study of economic deposits on the Moon and Mars. However, our understanding of the compositions, geological histories, and geological processes on those bodies will lead to significant differences in how we assess extraterrestrial ores. For example, the bone-dry nature of the Moon (except possibly at the poles) eliminates all ore deposits associated with hydrothermal fluids. The lack of strong evidence for plate tectonics on either the Moon or Mars (the apparent parallel magnetic anomalies on Mars notwithstanding) might render useless the recent terrestrial insights into ore deposition on Earth. In contrast, processes might have operated on the Moon or Mars, but not on Earth. These might have produced ores on those planets. For example, solar wind (hydrogen, helium, carbon, nitrogen) deposited in the lunar regolith (the upper few meters of the Moon) may be a crucial resource for lunar oxygen production, agriculture, and ^{3}He production. Thus, it will be important to develop a new classification for ore deposits for both the Moon and Mars, beginning with Guilbert and Park's (1) modification (their Table 8-4) of the classic Lindgren (2) classification of ore deposits. Without such a guide, it will be difficult to organize the search for resources on the Moon and Mars.

Table 1 outlines some of the localities where one might expect to find specific types of resources. This Table is modified greatly from Table 1-2 in Guilbert and Park (1). The point is not to show that we already know the answers, but to show the types of areas on the Moon and Mars we might investigate for specific types of resources. Note that any process that requires water did not operate on the Moon, so such resources will not be present. On the other hand, the Moon has the unique solar-wind deposits and likely contains a variety of metal deposits from igneous magmas. The Moon might have sufficient nitrogen in its regolith to use for agriculture, but it might be difficult to find sufficient phosphorus. Lunar farmers might find phosphorus in highly differentiated igneous rocks (3). Because water was at least intermittently present on Mars and now resides in its crust (4), it is likely that some hydrothermal and sedimentary ore deposits exist on the planet.

Although not listed in Table 1, aggregate will be an important resource on both the Moon and Mars (5). Aggregate is extremely important when building an infrastructure. It is the most mined material in the United States (2.3 billion tons a year). It is used for roads, concrete, bridges, roofing materials, and glass. On Earth, the main sources are sand and gravel deposits, and solid rock quarried to produce crushed stone. The lunar surface is essentially nothing but aggregate, so ample materials exist. However, it will be important to make a thorough search for unconsolidated aggregate on Mars (sand dunes are one possibility, debris at the base of cliffs another).

Search for resources using current data for the Moon and Mars. Prospecting can begin immediately. We have a wealth of remote sensing data for the Moon and Mars, with more Mars data on the way. In addition, we have a good sampling of the Moon by the Apollo and Luna missions, now supplemented by lunar meteorites, and we have an important collection of meteorites from Mars. We can target specific types of deposits already identified (e.g. lunar pyroclastics and hematite deposits in Sinus Meridiani, Mars) and look for other geological settings that might have produced ores and other materials of economic value. Another approach we will take is to examine all data available to look for anomalies. Examples are unusual spectral properties, large disagreements between independent techniques that measure the same property, or simply apparent exceptional properties such as elemental abundances much larger than anywhere else in a region.

Training the planetary economic geologists of the future: Effective and comprehensive resource exploration and prospecting on other planets will require the expertise of specially trained planetary economic geologists. Our plan includes developing a curriculum in planetary economic geology that will include hands-on exploration projects.

(1) Guilbert, J. M. and Park, C. F., Jr. (1986) *The Geology of Ore Deposits*. Freeman, 985 pp. (2) Lindgren, W. (1933) *Mineral Deposits*. McGraw Hill, N.Y., 930 pp. (3) Haskin, L. et al. (1993) A geochemical assessment of possible lunar ore formation. In *Resources of Near-Earth Space*, 17-50. (4) Wadhwa, M. (2001) Redox state of Mars' Upper Mantle and Crust from Eu anomalies in Shergottite pyroxenes. *Science*, **291**, 1527-1530. (5) Taylor, G. J. (2001) Human exploration for resources on Mars. *Workshop on Science and the Human Exploration of Mars*, LPI Contrib. No. 1089, 184-186. Lunar and Planetary Institute, Houston.

Table 1. Geological occurrence of important commodities on Earth and possible locations on the Moon and Mars.

Type of Occurrence	Main Commodities	Moon	Mars
Mafic igneous rocks	Cr, Pt-group, Ni, Ti	Central peaks of craters; crater rim deposits	Central peaks and ejecta of craters in highlands
Pegmatites	Ta, Nb, Be, Li	No	Possibly in highlands
Hydrothermal	F, Au, Ag, W, Cd, Bi, Hg	No	Volcanic systems, ancient highlands, large impact craters
Volcanic	Ag, Pt-grp, Zn, Hg, Pb, Cu	Pyroclastic deposits; near vent deposits in maria	Volcanoes, volcanic plains, possible pyroclastic deposits
Chemical sedimentation	Mn, Co, K, Fe, S, P	No	Ancient lake beds or hypothetical northern ocean; hematite deposit in Sinus Meridiani
Mechanical sedimentation	Th, Sn, Au	No	Outflow channels
Weathering	Al, Ni	No	Oldest surfaces with deepest soils, if there are soils
Solution-remobilization-deposition	K, Pb, U, V	No	Ground water systems; possibly in surface regolith
Space weathering	None	Solar wind gases in regolith; microscopic metallic iron	Organic compounds from micrometeorites