

TOWARD GEOCHEMICAL PROSPECTING FOR LUNAR ORES; L. A. Haskin,
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Ores are defined as economically valuable deposits. Before we can declare any lunar material to be an ore, we need to know the economics of its use, its concentration of the element or substance of interest, and how difficult it will be to extract or high-grade the element or substance of interest that it contains to the needed purity. This abstract is concerned with one part of this assessment--understanding the chemical systematics that will assist us in locating suitable ores and in estimating whether there is a material of high enough concentrations of a chemical element to be an ore.

The easiest elements to find in high concentrations are those making up the bulk of the regolith: O, Si, Al, Fe, Mg, Ca, Ti, and Na. We know what minerals contain them, what rock types contain those minerals, and, in a general sense, where those rock types are found. E.g., titanium and iron reach high concentrations in high-titanium mare basalts; locations of these are known from remote sensing (1-x). Since remote sensing techniques observe regolith, not bedrock, they actually locate regolith composed mainly of that rock type. This is beneficial, since tough basalt will not have to be mined and pulverized; meteoroid bombardment has already done that. There may be even more concentrated forms of titanium. From remote sensing as presently done, we observe concentrations averaged over broad regions. Pockets of very high concentration would exceed the resolution of our observations.

Some rocks consist principally or almost entirely of a single mineral; e.g., anorthosite consists almost entirely of plagioclase feldspar, the most common aluminous material likely to be present on the Moon. It is presumably abundant in the highlands; substantial samples were obtained by Apollos 15 and 16 and by Luna 20. However, there may not be convenient expanses of regolith consisting of nearly pure plagioclase. Remote sensing has located anorthosite in few locations, on steep slopes of a few craters or central peaks. The most concentrated regolith sampled was at Apollo 16, sta. 7.

Concentrations of some less abundant elements can be inferred from remote sensing data. These belong to the group that is excluded during crystallization of the major minerals of the crust and concentrated into the residual liquid. Examples of excluded elements are REE, Ba, Hf, Zr, and Ta. These have relatively high concentrations in KREEP. Excluded elements are excellently correlated with each other in our samples of the highlands regolith and, given the concentration of one, we can accurately calculate the concentrations of the rest. This is because many highlands materials are mixtures of rocks poor in these elements plus KREEPy materials. The gamma-ray experiment of Apollos 15 and 16 yielded relatively precise data for Th. If most of the Th in surface soils came from KREEP, then we know the distribution of concentrations of the other excluded elements. However, materials with the highest concentrations of, say, REE may deviate from the general pattern of correlation because, driven to extremes, processes of concentration may fractionate the relative abundances of KREEP. The gamma-ray data only provide average concentrations over broad areas. Concentrations within those areas may be much higher than the average.

In the maria, correlations among excluded elements are not general. E.g., LREE do not correlate with the HREE in all mare basalts. Mare basalts are not products of simple mixing, but derive from some combination of partial melting of a source region, fractional crystallization of melt prior to eruption, and perhaps assimilation of material from the conduits through which melts

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travel from depth before it erupts onto the surface. Mare basalts obtained so far fall into two categories with respect to excluded correlations--the Apollo 11 "low-K" and Apollo 17 basalts on the one hand, and the rest of the mare basalts on the other. Slopes of correlation lines for the basalts of this latter group are close to the concentration ratios of KREEP, indicating that melting and crystallization processes either did not disturb these ratios, which then must be characteristic of the lunar crust, or the melts assimilated sufficient of those elements during passage to the surface to obliterate whatever ratios they started with.

The large group of "vapor-transported condensate" elements (e.g., Br, Cd, Zn, Ag, Au, Rb) is apparently depleted in the lunar crust relative to Earth's crust and to chondritic meteorites. The highest observed concentrations of these elements are in rocks that rusted on exposure to Earth's atmosphere and on the surfaces of pyroclastic glasses. These elements apparently vaporize during heating processes, e.g., meteoroid impact and volcanic eruption, and condense onto debris or volcanic ash as it cools before falling to the surface. Concentrations of these elements correlate only roughly with each other. This may be related to small sample size, sample heterogeneity, low concentrations, and analytical difficulties. These elements have relatively high concentrations in Apollo 14 materials, the overall KREEPiest sampled location on the Moon. Correlations that do exist may arise in part because these elements are added to the regolith in significant quantities through meteorite bombardment. They may arise in part because the elements vaporize as a group during volcanic or impact heating. Refractory elements as LREE correlate reasonably well with some of the vapor-transported elements in Apollo 14 regolith samples. This suggests that the vapor-transported elements behaved as excluded elements during lunar differentiation and became concentrated into KREEPy materials. There may be deposits that have high concentrations of these elements owing to vapor transport and deposition, deposits whose concentrations do not correlate with those of refractory elements, but such deposits do not dominate the acquired samples.

Finding KREEPY elements or vapor-transported condensates in high enough concentration for use as ores will require that the processes of concentration that produced their observed relative enrichments have operated in an extreme manner in some regions. Those regions will have to have survived regolith bombardment so the resulting concentrates remain sufficiently intact to serve as ores. Considerations similar to the above also apply to other element groups. E.g., minor elements such as phosphates are concentrated into some anorthosites; manganese and titanium may have precipitated to form magmatic ores in lava lakes; and hydrogen, carbon, nitrogen, and noble gases are most concentrated in mature soils, owing to implantation from the solar wind. Much more consideration of lunar geochemical processes and of remote sensing clues is in order if we are to assess the probability for ores and guess intelligently where to find them.

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