Siderophiles in the lunar highlands crust: The lunar crust is essentially made up of igneous rocks, whose petrogenesis is significant in understanding the origin and evolution of the Moon. The elements Ni and Co are refractory and moderately siderophile, and in silicate magmatic systems are compatible elements. Hence the elucidation of their history is critical in understanding the Moon. Rocks actually identified as unmodified igneous are comparatively rare, the overwhelming majority of crustal rocks being impact-produced polymict breccias. Mixing models of polymict breccias require components in addition to known igneous rocks, and it has been suggested that these rocks are not at all representative of the crust and may even have lost Ni and some Co through metal segregation [1]. Thus attempts have been made to use the dominant polymict rocks to identify the Ni and Co of the crust [1, 2, 3, 4]. These methods have been used to suggest that the lunar highlands crust contains more indigenous Ni and Co than is suggested by the known igneous rocks, and in some cases to suggest that these abundances are high enough that the Moon is earth-like, with considerable ramifications for origin [e.g., 1, 2].

Meteoritic and indigenous components: Impacts that produce the mixing also add meteoritic siderophile elements, including Ni and Co, to the crust. Thus these methods rely on evaluating a meteoritic component and subtracting it to acquire a residual indigenous component. Others have shown that these methods have their flaws, and that selection of the meteoritic component to subtract is critically important [5, 6]. Further, some of these rely on over-simplified and dubious petrological concepts for the origin of crustal rocks. Alternatively, as in the method of [4], in an analogy of some terrestrial cases, a correlation lines among Ni, Co, and Ir in related samples (as will be used in this example, the Apollo 17 poikilitic melt rocks) is purported to have one endmember as the meteoritic component, the other as the lunar indigenous component. Here we show that this method is unlikely to produce correct results.

Data, correlations, and components: Figure 1 shows our data acquired by neutron activation for Ni, Co, and Ir for 22 samples (3 g allocations) analyzed in 18 of the Apollo 17 poikilitic melt samples. The Figure also shows data for known igneous rocks of the highlands. Palme [4] used the same example but with published analyses, including some aphanitic samples, but these are distinct samples even in Ni and Co and should not be included [7]. There is obviously a very good correlation among Ni, Co, and Ir, indicating two endmembers. Performing the same exercise as [4], with the acceptance that Ir is certainly almost entirely of meteoritic origin, then the extrapolations to the Ir-free ends of the correlation lines show that one component contains 0 ppb Ir, ~80 ppm Ni, and ~13 ppm Co. The other component can be equated with Fe-metal in these rocks, and contains all the Ir and much of the Ni and Co. However, unlike [4] we cannot equate these with indigenous components and meteoritic components.

Inferences: The metal is not of unaltered meteoritic origin. Figure 2 shows the same data as Figure 1 but with added information. The metal or high-Ir component is not of unmodified meteoritic origin; it is clearly much lower in Ni/Co (Fig. 2c, 2d) than a meteoritic component (which is rather like an EH chondrite according to trace elements [e.g., 8]). The metal has also clearly taken up P and W for instance. Thus the metal has re-equilibrated with a new silicate system formed from mixing meteoritic and indigenous components. This new metal has extracted some indigenous Ni and Co. The lower end of the correlation line is thus not an indigenous component, but is the residue left in the new system after high-Ir metal extraction. The figures show that a mix of rocks like the known igneous rocks with an EH chondrite can provide an average composition which can then produce the known metal except that it admittedly requires more Ni than most igneous rocks can provide. (Unfortunately there is only one analysis for Ir in the actual metal in these samples and it seems at odds with the correlation line and may be anomalous). The analyses spread among rocks, and it is clear that there is a difference in metal abundance among rocks. This has fractionated the meteoritic component, and each rock sample is actually unrepresentative for the moderately siderophile elements compared with the average. This has the unfortunate effect of making computational mixing models of individual samples “challenging”, because they do not have an unmodified meteoritic component to subtract. Thus component identifications based on Ni and Co are open-ended.

Location of Ni and Co: Much of the Ni and Co is in the iron metal, but the other component still contains some of these elements. We have used the microprobe to try to identify where these elements reside, using 20 keV, 100nA, and long counting times. Uncertainties are ~ 30 ppm. The silicates contain negligible Ni or Co, other than some olivines contain 50-100 ppm Ni, but at <10% they cannot provide the Ni. Some sulfides contain as much as 2000 ppm Ni and high Co, but their abundance is so low that they too, with the silicates, cannot provide more than about 20-40 ppm of the 80 ppm Ni we seek. It appears that the Ni is well distributed among major phases in general; it also may reside in some residual (Ir-free) metal.

Fig. 1a: Apollo 17 poikilitic melts vs. Lunar highlands pristine rocks

Fig. 1b: Apollo 17 poikilitic melts vs. Lunar highlands pristine rocks

Fig. 1c: Apollo 17 poikilitic melts vs. Lunar highlands pristine rocks

Fig. 1d: Apollo 17 poikilitic melts vs. Lunar highlands pristine rocks