EVIDENCE FOR METAMORPHIC Pb IN ANCIENT LUNAR HIGHLAND ROCKS (>3.9 Ga) ?: AN ALTERNATIVE EXPLANATION FOR "UGLY" U-Pb SYSTEMATICS;

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A plot of Mg' vs $^{207}Pb/^{206}Pb$ using the limited present database for non-mare, probably-pristine, ancient lunar rocks [1] illustrates an inverse correlation between the two parameters; i.e. low-Mg highland rock types (e.g. ferroan anorthosites) have significantly higher $^{207}Pb/^{206}Pb$ values than high-Mg rocks. The fact that anorthosites contain >90% plagioclase by volume compared to the variable, but notably smaller, proportions of plagioclase in high-Mg rocks (e.g. norites, troctolites, dunite, gabbros) probably has a great deal to do with these statistics. If reduced Mg numbers or MgO and FeO values in anorthositic plagioclase is a metamorphic signature as suggested by [2], then the correlation implies that high $^{207}Pb/^{206}Pb$ values are also metamorphic. If this is so, the only presently identifiable source for the high $^{207}Pb/^{206}Pb$ values is high-μ (>1000) KREEP. To this point, high-μ magmas were thought to be the source of ferroan anorthosites and high-Mg suite rocks [3], although alternative explanations had been mentioned. But if this is not the case, then this Pb had to either have been added metasomatically as suggested by [4] or it is metamorphically emplaced during major impacting as implied by [2]. So the question is: how and when did KREEP Pb get into ancient lunar highland rocks ?

Last year, in an imprompt to poster session presentation, we summarized the present database of Pb isotopic data for ancient (>3.9 Ga) lunar highland rocks, illustrating that there appears at least three distinct major, magma-producing reservoirs (with respect to U-Pb) that existed during the first 500 m.y. of the Moon's history [5]. One of these major magma reservoirs apparently continued to evolve in the upper mantle reservoir (~4.1 to 4.36? Ga) and form magmas or liquids with progressively increasing μ values between ~300 and >1000. The fact that most of the ancient lunar crustal rocks, thought to have been derived from this magma reservoir, exhibit high $^{207}Pb/^{206}Pb$ values and corresponding high-source μ values has however always been a problem. It is hard to reconcile the formation of such extreme U/Pb fractionations given starting conditions two orders of magnitude smaller as well as trying to understand this KREEP-like Pb component coexisting in a system defined so differently by the rest of the major and trace element geochemistry. We had previously ruled out metamorphic Pb contamination because of the level of probable pristinity of the samples analyzed [1] and because during leaching of these samples using a variety of dilute acids, the Pb isotopic compositions of subsequent leaches as well as the final residue would often be more radiogenic with even higher $^{207}Pb/^{206}Pb$ values, indicating that this Pb composition is probably primary. However, in light of the possibility of metamorphic substitution of major elements as well as minor ones in anorthositic plagioclase [2] - the correct interpretation of the Pb data has far-reaching implications regarding the evolution of early lunar magmas.

In figure 1 below, $^{207}Pb/^{206}Pb$ values [3] for several possibly-pristine lunar highland rock samples are compared with the Mg' from their low-Ca pyroxene [1]. Some ferroan anorthosite whole-rocks and all the plagioclase (except 60025) have $^{207}Pb/^{206}Pb$ values between ~1.0 and 1.5, corresponding to low Mg's. This characteristic is in marked contrast to the data for high-Mg suite whole-rocks and magnetic mineral separates (e.g. pyroxene, olivine) that show relatively low $^{207}Pb/^{206}Pb$ values (0.48 to 0.72) with corresponding high Mg's. If the reduction in Mg' is due to excess MgO loss with respect to FeO during thermal metamorphism [2], then it opens the possibility that the Pb in these rocks, and in particular the ferroan anorthosites, is metamorphic as well. This possibility actually makes life in the lunar U-Pb world easier to understand. If the Pb in these rocks is metamorphic, several key observations can be made from the figure: (1) Ferroan anorthosites show the most consistent high $^{207}Pb/^{206}Pb$ values because they are essentially all plagioclase which is a Pb sink compared to the other mineral constituents of the lunar highland rocks; their whole-rock Pb values nearly match the plagioclase Pb values, (2) The magnetic mineral separates from these anorthosites do not show significant variations in Pb isotopic values (e.g. 67075 or 60025) because they do not accept appreciable amounts of Pb. In fact, a metamorphic event should cause Pb loss in these mineral separates. A plot of the U-Pb data for the magnetic mineral separates of ferroan anorthosites should produce much better results, (3) 60025 is the best behaved of the ferroan anorthosites, although it too shows some elevated $^{207}Pb/^{206}Pb$ values, particularly in some of the plagioclase separates, and (4) some plagioclase separates (and even a magnetic separate from dunite 72415) of high-Mg suite rocks show elevated $^{207}Pb/^{206}Pb$ values, suggesting that these rocks are affected as well.

The real difficulty with this situation, however, lies in the fact that the amount and isotopic composition of the Pb contaminant may vary from grain to grain (or possibly within grains) of any one of these samples, and attempts to separate them for U-Pb analysis would essentially be mixing the "older" Pb contaminant with the original, primary Pb of the sample in various proportions that would make it near impossible to accurately correct these analyses. The magnetic mineral separates of course offer the best possible results, because they were so Pb-poor to begin with, corrections for their U-Pb data are very small.

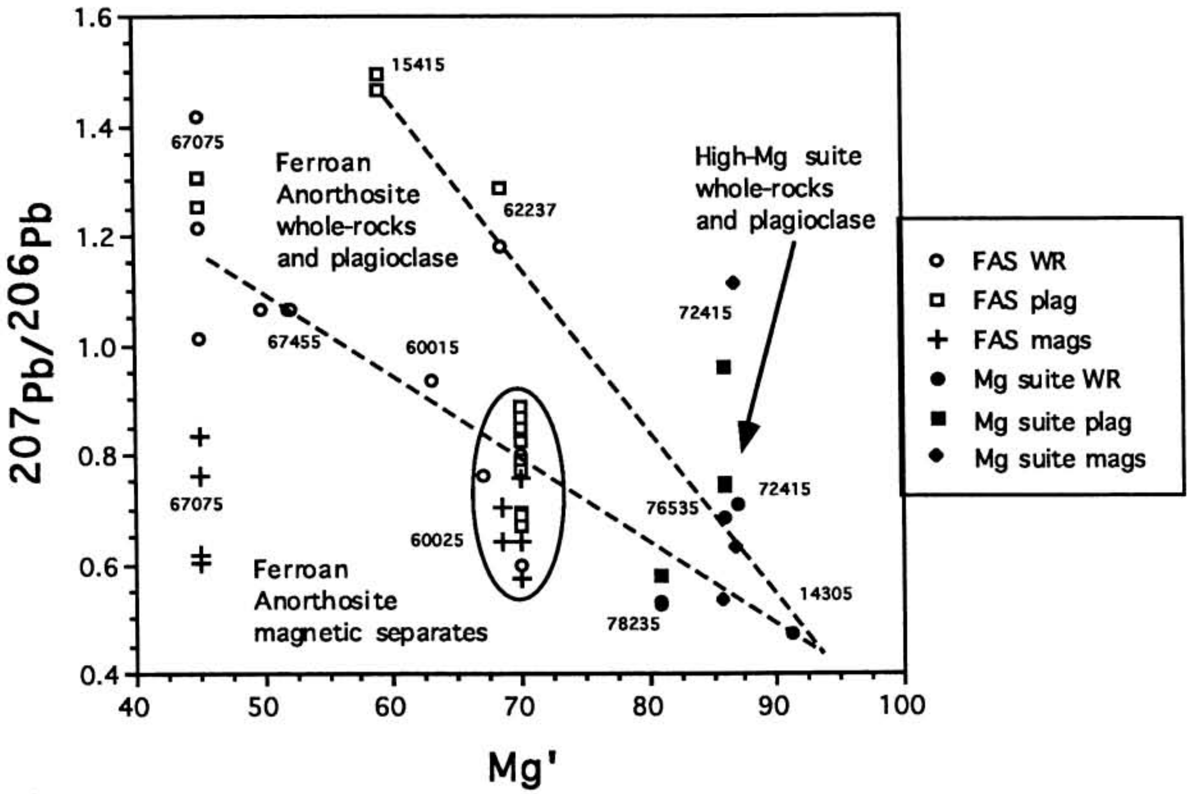

Figure 1: Pb isotopic data for various non-mare highland rocks compared with their low-Ca pyroxene Mg'.

If it is true that the high $^{207}Pb/^{206}Pb$ values are metamorphic, the only presently identifiable source for them is high-μ (>1000) KREEP, which would either have been added or exchanged metasomatically as suggested by [4] or metamorphically emplaced during major impacting as implied by [2]. Our present suggestion is that the Pb is metamorphically emplaced during major impacting, probably during the 3.9-Ga cataclysm [5]. Such an event would have produced the energy required to reactivate and spread KREEP Pb throughout crustal rocks all over the lunar near-side. If KREEP Pb had been exchanged metasomatically, we would not expect to find evidence of it in the gabbroic lunar meteorite, Asuka 881757 [6], dated at 3.9 Ga. The ubiquity of the high $^{207}Pb/^{206}Pb$ values is therefore an artifact of the Apollo and Luna sampling sites, all located on the near-side of the Moon that was obviously deeply excavated during the basin-forming event(s).

References: [1] Warren P.H. (1993) Amer. Mineral. 78, 360. [2] Phinney, W.C. (1994) LPS XXV, 1081. [3] Premo W.R. and Tatsumoto M. (1995) LPS XXVI, this volume. [4] Neal C.R. and Taylor L.A. (1991) Geoch. Cosmo. Acta 55, 2965-2980. [5] Tera F. et al. (1974) EPSL 22, 1-21. [6] Misawa K. et al. (1993) Geoch. Cosmo. Acta 57, 4687-4702.