U-Pb ISOTOPIC AGES AND CHARACTERISTICS OF ANCIENT (>4.0 Ga) LUNAR HIGHLAND ROCKS; W.R. Premo, U.S. Geological Survey, MS 963, Box 25046, Federal Center, Denver, CO 80225

A review of the present (and certainly sparse) U-Pb isotopic database for ancient (>4.0 Ga) lunar highland rocks indicates that both early-forming anorthosites and high-Mg suite rocks were formed from sources with a wide variety of $^{238}U/^{204}Pb$ (μ) values as early as 4.44 Ga. The U-Pb data from Apollo 16 anorthosites 67075, 60025, and 62337 [1,2] indicate source-μ values between ~35 and ~350; whereas values for high-Mg suite rocks are tentatively considered to be over 500 [3,4,5], similar to KREEP sources [6]. At present, I interpret the data to indicate that either early cumulates were formed slowly in a magma environment that allowed isotopic reequilibration or mixing over a long period of crystallization, or these cumulates formed from rapidly-evolving (both geochemically and isotopically) residual liquids. It is also possible that an early bombardment period played a role in the mixing process.

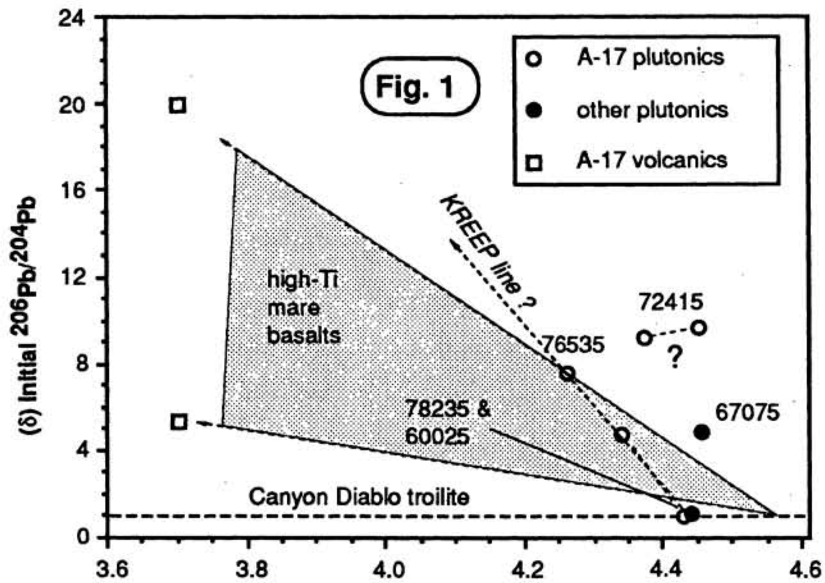
Four different decay schemes, K-Ar, Rb-Sr, Sm-Nd, and U-Pb, have predominantly been used for age determinations on lunar rocks. Each of these systems is not without problems when applied to lunar samples. In order for any single radiometric system to yield a primary crystallization age, it must remain closed from the time of crystallization until the present, without addition or loss of either parent or daughter isotopes. After many years of isotopic work, investigators have come to realize that most lunar samples (nearly all ancient highland samples) have been metamorphosed and their isotopic systematics disturbed [7]. U-Pb and Th-Pb isochron ages of lunar samples typically date metamorphic events [3]. Fortunately, there are two U-Pb systems that can be compared simultaneously in a concordia diagram to "look through" disturbances. This attribute of the U-Pb systems is most desirable when working with lunar samples, and helps to identify both the age of the rock and the age of the disturbance. A major drawback of this approach is the necessity for initial Pb corrections in order to calculate radiogenic Pb/U ratios [3]. Initial Pb compositions are typically defined by the y-intercepts on U-Pb and Th-Pb isochron diagrams, but because most U-Pb and Th-Pb isochrons for lunar samples are disturbed, the initial Pb values are undefined and therefore must be assumed. This situation has been confronted with norite 78235 [4] and troctolite 76535 [3]. A possible solution to the problem is to use an age (hopefully accurate), perhaps determined using one of the other dating techniques, and calculate the initial Pb values that produce the same age with the two U-Pb systems. Whereas this procedure relies on an accurate age for the rock, the resulting initial Pb information can be used to characterize the source magma as is done with initial Sr and Nd values, and can have important implications for models of the petrogenesis of lunar magma sources through time.

Because the various isotopic systems are disturbed differently during metamorphism, most samples yield conflicting ages when using the different dating schemes on the same sample. Whereas the discrepancy in ages is usually interpreted as a result of open-system behavior due to metamorphic disturbances that characterize lunar rocks, other factors may cause age disparity as well, including either the misuse of basic assumptions regarding the isotopic techniques (e.g. U-Pb), or a lack of understanding of lunar petrogenesis (isotopic closure ages vs. ages of crystallization), or a combination of these factors. One possibility that cannot be dismissed is whether the disparity in ages reflects very slow cooling and crystallizing of the parent magma, particular at depth in the lunar crust, and therefore the differences in isotopic closure temperatures of the various radiometric systems rather than the age of crystallization of the rock [4,7]. The isotopic data from ancient highland samples collected during the Apollo missions have many of these problems, so that at present investigators have only a very limited, reliable (as well as precise), isotopic database to work from. Interpretations on the magmatic ages and origins of at least the ancient highland rocks are therefore tentative at best.

Over the past five years we have analyzed Apollo 16 anorthosites 67075, 60025, and 62337 [1,2] and Apollo 17 high-Mg suite cumulates (troctolite 76535 [3], norite 78235 [4], and dunite 72415 [5]) in an effort to discover an earliest lunar Pb isotopic composition and accompanying U/Pb value, both of which may have important implications on our understanding of early lunar magmatic processes and evolution of a magma ocean. In general, U-Pb isotopic systematics are better behaved in the high-Mg suite rocks than in anorthosites that have shown evidence of mineral assemblages of mixed parentage [1,2,8]. Our results strongly suggest that plagioclase assemblages of the ferroan anorthosites, although geochemically uniform [8,9], are derived from isotopically different sources (μ = ~35 but up to ~350), but essentially during the same geologic event (formation of an outermost feldspathic crust) between 4.42 and 4.45 Ga [2,10]. Magnetic mineral assemblages, including olivines and pyroxenes, may or may not have crystallized at this same time. Most of the U-Pb isotopic evidence from magnetic mineral separates indicate that they are either derived from distinctly different liquids (isotopically speaking) than some of the plagioclase separates or formed at a younger time [2]. For example, one magnetic separate from anorthosite 60025, M-1, contains material that is younger than the plagioclase and may have been derived from a source with μ ~12 at 4.32 Ga.

The oldest high-Mg suite rocks are norite 78236 (assuming 4.425 Ga age) and dunite 72417 at ~4.45 Ga. These rocks are then followed by norite 77215 (~4.37 Ga), troctolite 76535 (~4.26 Ga), gabbronorite 73255 (~4.23 Ga), and norites 73215 and 78155 (~4.17 Ga), although the latter may not be primary ages. Accepting these minimum estimates, high-Mg suite formation appears to have continued from ~4.45 to ~4.15 Ga [7]. However, depending on the investigators interpretation of the isotopic age data, it is also possible to consider a much smaller magmatic interval. For example, we might question the Rb-Sr isochron age for dunite 72417, largely dependent on the mineral, olivine, previously noted to be highly altered and possibly isotopically unreliable or disturbed [5] in some of these samples. A "best guess" Pb-Pb age of ~4.37 Ga was reported by [5] for 72415. Conflicting Sm-Nd isochron ages of 4.43 and 4.34 Ga are not supported by other isotopic age results, resulting in some uncertainty of the true age of norite 78236 [7]. If we accept the younger age for this norite and assume that 73215 and 78155 are probably older than 4.17 Ga, then we find that most of the noritic-troctolitic (and probably dunitic) ages lie within a range of ~140 million years (4.37 to 4.23 Ga).

From these ages, we can construct Pb evolution curves for ancient lunar highland rocks as shown in Fig. 1. The initial $^{206}Pb/^{204}Pb$ (R) data is normalized ($\delta = R_m / R_{CD}$) to Canyon Diablo (CD) troilite ($\delta = 1$). The Pb isotopic data is too sparse and imprecise to make confident generalizations; however, the coherence of the data between anorthosite 60025 and norite 78236 would suggest that high-Mg suite rocks and ferroan anorthosites were both forming simultaneously during differentiation of the lunar magma ocean. Large uncertainties in the U-Pb data of 67075 and 72415 leaves these analyses in question, although an unpublished Sm-Nd internal isochron age of 4455 ± 140 Ma for 67075 indicates that it was also formed early. An interesting line of ascent is indicated by anorthosite 60025, norite 78235/6, and troctolite 76535, suggesting derivation from magma sources that are progressively evolving to higher $^{238}U/^{204}Pb$ and corresponding initial $^{206}Pb/^{204}Pb$ values, similar to the Sm-Nd KREEP line [7].



I tentatively suggest that either early cumulates were formed slowly in a magma environment that allowed isotopic reequilibration or mixing over a long period of crystallization, or these cumulates formed from rapidly-evolving (both geochemically and isotopically) residual liquids. It is also possible that an early bombardment period played a role in the mixing process.

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