
We believe the present volume of Pb isotopic data from various samples of non-mare lunar rocks (>3.9 Ga) indicates at least three isotopically distinct reservoirs that produced magma sources for the lunar crustal rocks that formed over the first 500 m.y. of lunar history. An early, presumably magma ocean-type source that existed 4.42 to 4.44 Ga is characterized by 238U/204Pb (μ) values varying between 35 and 100 [1] and probably produced the early plagioclase-rich lunar crust [2]. A later (~4.1 to 4.42 Ga), probably upper lunar mantle reservoir continued to evolve and formed magmas or liquids with progressively increasing μ values between ~300 and >1000 [3,4,5,6]. After the early reservoirs were exhausted and most of the lunar crust and upper mantle were emplaced, a lower lunar mantle reservoir continued to develop (at least as old as 3.9 Ga) and produced magmas with relatively low-μ values between 10 and 50. The fact that most "old" lunar crustal rocks exhibit high 207Pb/206Pb values requires that they were either derived from, mixed with, or contaminated by Pb produced from early-formed, high-μ magma sources. The ubiquity of these U-Pb characteristics may also be 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), suggesting that the Pb signature in these rocks may be metamorphically emplaced [7].

For the past eight years, the Denver Isotope Group has worked to identify the earliest lunar Pb isotopic compositions and corresponding U/Pb values we believe will help in understanding early lunar crust-mantle evolution. With this goal in mind, we have analyzed a variety of Apollo 16 anorthosites [1,8]; Apollo-17 high-Mg suite cumulates [5,6,9,10]; Apollo 15 green glass [11]; and various lunar meteorites [12,13,14]. In figure 1, we show these data along with Pb isotopic data from the literature [10,15,16,17,18,19,20,21]. The data are mostly from residues of whole-rocks and mineral separates of various non-mare samples including cataclastic anorthosites, norites, gabbronorites, granitic clasts, breccias, glasses, and soils. Several of the more pristine, monomict samples have fairly well-established ages [22], but most are of uncertain age and assumed to be between 3.9 and 4.45 Ga old.

The residue data scatter inside a triangle defined by the Pb composition(s) at "A", the radiogenic Pb compositions of these type of rocks found right above "B", and a non-radiogenic composition(s) that for these rocks only begins to approach "C", "D", or CDT. Essentially all of the Pb data can be explained as mixing between these three basic Pb components or isotope reservoirs. Pb in lunar rocks usually is a mixture of primary and secondary Pbs [6]. Secondary Pbs are introduced by contamination using one mechanism or another, but usually by extraterrestrial mixing and/or terrestrial handling. These Pbs are thought to be greatly reduced during leaching of lunar samples using a variety of dilute acids, leaving only primary Pbs to be analyzed [6]. Primary Pbs are of two types, radiogenic (accumulated from the in situ decay of U and Th since the time of rock formation) and initial (Pb that was incorporated in the rock at the time of formation). Initial Pb can have a wide variety of compositions depending on the U/Pb value and age of the source from which the rock crystallized. In figure 1, the data just above "B" represents radiogenic Pb components, so that the 207Pb/206Pb value of the sample indicates the age, typically between 3.9 and 4.45 Ga. Initial Pb compositions for these rocks can be represented by the Pb evolution curves shown between "A" and "D". These curves (one-stage and three-stage) illustrate the change in Pb composition that might be found in source(s) at 4.23 Ga (chosen to satisfy the systematics of 76535 that lie on this array) depending on their μ values since 4.56 Ga (assumed age) and starting with the primitive Pb composition of CDT. The bulk of the data lie along three arrays. Chronologically, the first array (between "B" and "C") is mostly defined by some of the plagioclase separates of anorthosite 60025 [1], although other sample separates are similar, and yield a 207Pb/206Pb age of 4421 ± 74 Ma (dashed line). Other plagioclase separates from a large chip of 60025 lie on a different array, but yield essentially the same age (4431 ± 15 Ma). Despite the apparent polymictic nature of 60025, we believe this anorthosite is unique in that its Pb isotopic systematics require that it was formed from a geochemically uniform [23], but isotopically heterogeneous (μ between ~35 and 100) source(s) ("C"; Fig. 1). If this anorthosite (or at least the plagioclase from it) represents a cumulate product formed during the Moon's early primary differentiation stage, then that source was presumably the magma ocean.

The second array (between "A" and "B") includes most high-Mg suite rocks/minerals, but also some anorthosites, most evolved rocks, and numerous breccias and soils. This array represents mixing between radiogenic Pb at "B" and an "old" initial Pb at "A". The incorporation of the "old" Pb in these samples is problematic in that some samples appear to have been derived from a magma with this Pb composition (e.g. 15415; [24]), whereas other samples appear to have had this Pb adsorbed to them [6, 8]. It is also possible that...
Figure 1: Pb-Pb isotopic data for various non-mare basalt rocks. Pb evolution curves show the loci of Pb values for lunar sources with \( \mu \) values between 10 (at CDT: Canyon Diablo troilite Pb) and 600 (near "A") from 4.56 Ga as the age of the Moon and ~4.23 Ga (age of troctolite 76535). For samples with reasonably well-established ages, \( \mu \) values vary between ~10 (lunar meteorite, Asuka 881757 [13] and >1000 (evolved rocks and high-Mg suite rocks with KREEP-like components). See text for further discussion.

This Pb was added metasomatically after cumulate formation [e.g., 25] or metamorphically emplaced [7]. Regardless of how the Pb is incorporated, a reservoir characterized by KREEP-like, high-\( \mu \) values must have existed in order to produce such high \( ^{207}\text{Pb}/^{206}\text{Pb} \) values. Since some of the samples appear to be older than 4.3 Ga, the formation of this high-\( \mu \) reservoir must have occurred during late lunar differentiation.

A third array (between "B" and "D") was recently defined by work on lunar meteorites Asuka 881757 [13] and Yamato-793169 [14] and indicates that their source(s) had low-\( \mu \) values ~10. Since we know the age of these rocks to be ~3.9 Ga, low-\( \mu \) magma source(s) existed at that time, probably in the lower lunar mantle, and are confirmed by \( \mu \) values from green glass [11], derived from the deep lunar mantle (400 ±50 km; [26]). The fact that we do not find any of these low-\( \mu \) samples in the Apollo-Luna collection is probably due to their lunar near-side affinity. Low-\( \mu \) crustal rocks are apparently absent due to either their removal or reequilibration during the 3.9-Ga cataclysm [19] that exposed and spread KREEP-rich, lower crustal rocks all over the lunar near-side.