Sm-Nd AND Rb-Sr ISOTOPIC STUDIES OF METEORITE KALAHARI 009: AN OLD VLT MARE BASALT.

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Introduction: Lunar meteorite Kalahari 009 is a fragmental basaltic breccia containing various VLT mare basalt clasts embedded in a fine-grained matrix of similar composition [1-2]. This meteorite and lunar meteorite Kalahari 008, an anorthositic breccia, were suggested to be paired mainly due to the presence of similar fayalitic olivines in fragments found in both meteorites [1]. Thus, Kalahari 009 probably represents a VLT basalt that came from a locality near a mare-highland boundary region of the Moon, as compared to the typical VLT mare basalt samples collected at Mare Crisium during the Luna-24 mission. The concordant Sm-Nd and Ar-Ar ages of such a VLT basalt (24170) suggest that the extrusion of VLT basalts at Mare Crisium occurred 3.30±0.05 Ga ago [3]. Previous age results for Kalahari 009 range from ~4.2 Ga by its Lu-Hf isochron age [2] to 1.70±0.04 Ga of its Ar-Ar plateau age [4]. However, recent *in-situ* U-Pb dating of phosphates in Kalahari 009 defined an old crystallization age of 4.35±0.15 Ga [5]. The authors suggested that Kalahari 009 represents a cryptomaria basalt. In this report, we present Sm-Nd and Rb-Sr isotopic results for Kalahari 009, discuss the relationship of its age and isotopic characteristics to those of other L-24 VLT mare basalts and other probable cryptomaria basalts represented by Apollo 14 aluminous mare basalts [e.g. 6], and discuss its petrogenesis.

Samples and Analytical Procedures: A thin slab of Kalahari 009, weighing ~0.52 g was processed for isotopic study. The sample was first sonicated in ethanol to remove surface contaminants, and then crushed gently to pass a nylon sieve of opening size <149 µm. About 86 mg was taken as the bulk rock sample (WR). The rest of the sample was sieved into 149-74 µm, 74-44 µm and <44 µm size fractions. A plagioclase sample (Plag) and an opqaues-olivine mixture sample (Opq) were separated from the 149-74 µm fraction by Franz magnetic separator. Further density separation of this fraction is in progress. We obtained pyroxene and olivine from the 74-44 µm fraction using heavy liquids. We obtained an impure pyroxene sample (Px1) from the 2.85-3.32 g/cm^3 density fraction. A purer pyroxene sample (Px2) was separated from the higher density fraction (3.32-3.7 g/cm^3). A small olivine sample (Ol) was obtained from the fraction with a density greater than 3.7 g/cm^3. To remove terrestrial contaminants (mostly calcites [1]) due to desert weathering, the bulk rock and all mineral samples were washed with either 1N HCl (for Plag, Opq and Ol) or 2N HCl (for Px1, Px2 and WR) in an ultrasonic bath for 10 minutes. Both the WR and mineral residues (r) and WR leaches (l) of these samples were analyzed. The acid washes from all minerals (Leach) were combined and also were analyzed.

Sm-Nd isotopic results: Fig. 1 shows ^{147}Sm/^{144}Nd and ^{143}Nd/^{144}Nd data for six bulk rock and mineral samples of Kalahari 009 analyzed so far. The Sm-Nd data form a linear array yielding an age of 4.30±0.05 Ga for $\lambda(^{147}\text{Sm})=0.00654$ Ga^{-1} and an initial $\varepsilon_{Nd}=+0.83\pm0.47$ relative to the chondritic reservoir (CHUR) of [7] or initial $\varepsilon_{Nd}=-0.04\pm0.47$ relative to the eucritic reservoir (HEDR) of [8, 9]. Our Sm-Nd isochron age for Kalahari 009 is in good agreement with the U-Pb age of 4.35±0.15 Ga for phosphates in the clast [4] and the Lu-Hf isochron age of ~4.2 Ga [2], suggesting that the VLT basalt crystallized ~4.30 Ga ago. The Kalahari 009 sample is one of a few ancient mare basalts found so far. Two other similarly old mare basalt samples are an olivine basalt clast 14305,122 [10] and a Group 5 aluminous mare basalt (AMB) 14321, 9059 [11, 12]. Their Rb-Sr isochron ages are 4.19±0.05 Ga and 4.30±0.17 Ga, respectively, adjusted for the preferred $\lambda(^{87}\text{Rb})$ of 0.01402 Ga^{-1}. Thus, the Kalahari VLT mare basalt volcanism is probably contemporaneous with some of the A-14 aluminous mare basalt volcanism.

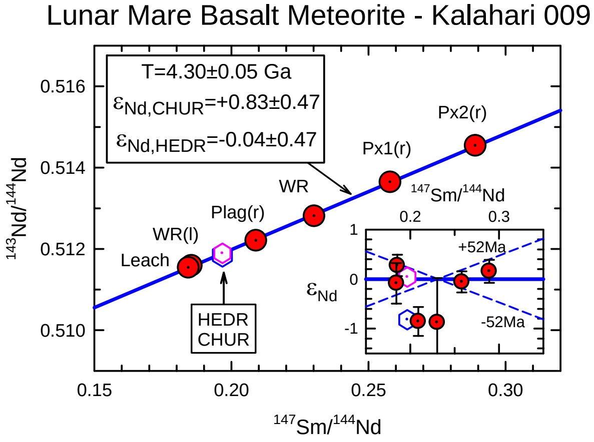

Figure 1. Sm-Nd data for Kalahari 009.

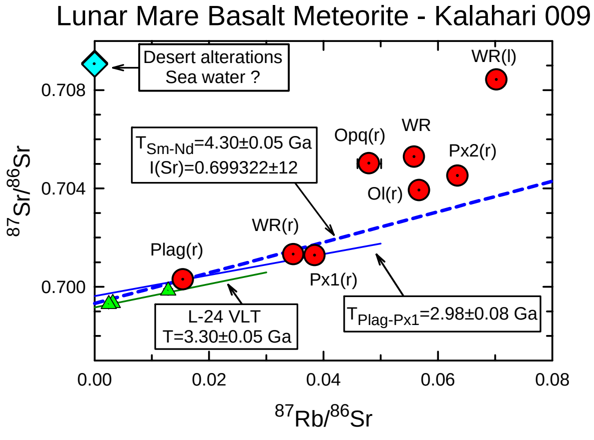

Figure 2. Rb-Sr data for Kalahari 009.

Remote-sensing analyses of TiO_2 and FeO distributions of dark-haloed deposits of ancient lunar craters suggest cryptomaria basalts do not include high-Ti mare basalts, but are either mostly low-Ti to VLT mare basalts, or AMB [*e.g.* 6].

Therefore, both VLT and AMB basalts could be samples of the cryptomaria.

Rb-Sr isotopic results: The ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr data for eight Kalahari 009 samples are shown in Fig 2. Unlike in the Sm-Nd isotopic system, the Rb-Sr isotopic data are so scattered that no Rb-Sr isochron, and thus, no independent age can be obtained from these samples. Because the Plag(r) sample has the highest Sr content, its Sr isotopic composition is probably least affected by desert alterations. A good estimate of the initial ^{87}Sr/^{86}Sr =0.699322±12 (λ(^{87}Rb) =0.01402 Ga^{-1}) for Kalahari 009 can be made using the Plag(r) datum and the Sm-Nd isochron age of 4.30 Ga (Fig. 2). Most samples plot above this 4.3 Ga Plag(r) reference isochron (blue dotted line), indicating that all the samples, even those washed with acids, still contain significant amounts of desert contaminants. The present-day sea water value of ^{87}Sr/^{86}Sr =~0.709 (blue diamond) is plotted to approximate possible desert contaminants. The linear array for three data, Plag(r), WR(r) and Px1(r), yields a younger age of ~3.0 Ga, which is a partially reset age because the meteorite was probably brecciated at 1.70±0.04 Ga ago as indicated by its Ar-Ar degassing age [4].

Petrogenetic implications: The initial ^{87}Sr/^{86}Sr, I(Sr), and ages of L-24 VLT (green diamond), as well as various groups of A-14 AMB (yellow parallelograms) are summarized in Fig. 3. The data are from [13]. The red dot symbolizes our best estimated I(Sr) and age data for Kalahari 009. Dotted lines represent a two-stage calculation of the time-averaged ^{87}Rb/^{86}Sr sources (μ) for these basalts. Kalahari 009 plots between the ^{87}Sr in-growth lines for AMB and KREEP basalts, implying a close petrogenetic relationship with those basalts. Clearly, there are at least two types of VLT basalts. One is young (~3.3 Ga) and was derived from a low-μ (~0.012) source and is associated with mare basins. This type of VLT basalt is represented by L-24 basalt 24170 [3]. Other VLT basalts are ancient (~4.3 Ga), as represented by Kalahari 009, were derived from high-μ (~0.09) sources, and are associated with A-14 AMB and KREEP basalts commonly found near highland regions,. The young VLT originated from depleted cumulates whereas the old VLT probably came from a trapped liquid (~urKREEP) -contaminated cumulate source, similar to the source of A14 AMB [15].

Fig. 4 summarizes the ε_{Nd}-values and ages of two types of VLT basalts, L-24 (green diamond) and Kalahari (red dot), as well as A-14 AMB (yellow area) and highland KREEP basalts (purple triangles). The data are from [13]. For lunar Nd isotopic evolution, we adopted the HED Reservior (HEDR) value of [8, 9] as the initial ^{143}Nd/^{144}Nd parameter. Recent measurements of Nd isotopes of chondrites suggested the Earth (Moon also?) is non-chondritic in ^{142}Nd/^{144}Nd [14], probably also in ^{143}Nd/^{144}Nd [8, 9]. The HEDR value is ~0.87ε higher than the CHUR value [7]. The dotted lines represent time-averaged source ^{147}Sm/^{144}Nd (μ) values for a two-stage model for these basalts. Again, Ka 009 plots close to the A14 AMB field, but is distinct from the KREEP–norite evolution line (red line). Relative to the HEDR, young L-24 VLT were derived from a slightly superchondritic ^{147}Sm/^{144}Nd source with μ=~0.21, i.e., a slightly LREE-depleted source, whereas the old Kalahari VLT came from a nearly chondritic Sm/Nd source (μ=~0.196). Our Nd isotopic data do not preclude the presence of an urKREEP component in the Kalahari VLT cumulate source region, as proposed for the A14 AMB petrogenesis [15]. The similarity in old ages and source characteristics confirms that both VLT and AMB are cryptomaria basalts. A possible cryptomare for Kalahari 009 would be the Lomonosov-Fleming basin, northeast of Mare Marginis, where both VLT and AMB might exist [6].

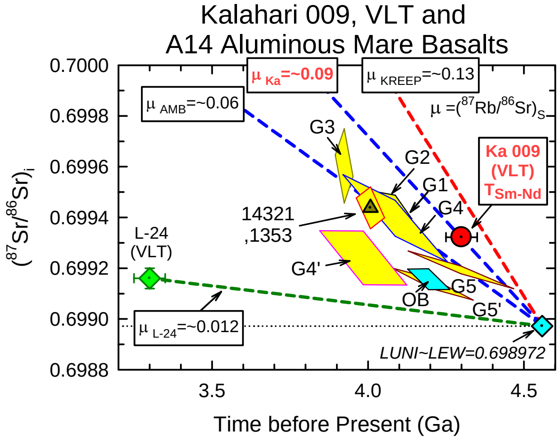

Figure 3. I(Sr) vs. T(age) of Kalahari 009 (red), L-24 VLT (green) and various groups of A14 AMBs (yellow).

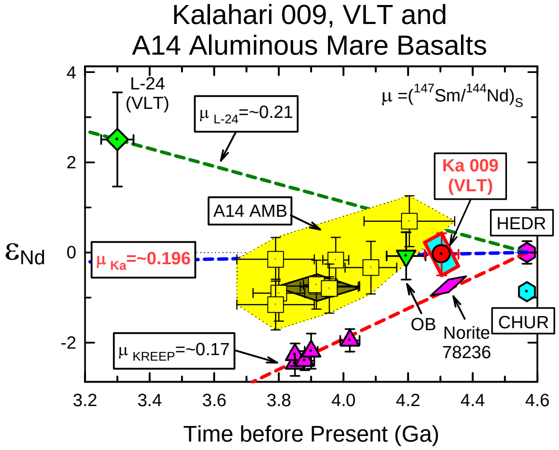

Figure 4. ε_{Nd} vs. T(age) of Kalahari 009 (red), L-24 VLT (green) and A14 aluminous mare basalts (yellow).

References: [1] Sokol A.K. and Bischoff A. (2005) *Meteoritics Planet. Sci.* **40**, A177-A184. [2] Schulz T. *et al.* (2007) *Meteoritics Planet. Sci.* **35**, A178. [3] The Lunatic Asylum (1978) *Mare Crisium: The views from Luna 24*, Pergamon Press. 657-678. [4] Fernandes V.A. *et al* (2007) *XXXVIII*, CD-ROM #1611. [5] Terada K. *et al.* (2007) *Nature*, **450**, 849-852. [6] Hawke B.R. *et al.* (2005) *LPS-XXXVI*, CD-ROM #1642. [7] Jacobsen S.B. and Wasserburg G. J. (1984) *EPSL 67*, 137-150. [8] Nyquist L.E. *et al.* (2004) *28th Symp. Antartic. Met.* 66-67. [9] Nyquist L.E. *et al.* (2008) *LPS-XXXVI*, this volume. [10] Taylor L.A. *et al.* (1983) *EPSL*, **66**, 33-47. [11] Dasch E.J. *et al.* (1987) *GCA*, **51**, 3241-3254. [12] Dickinson T. *et al.* (1985) *12th LPSC, JGR*, **90**, C365-C374. [13] Nyquist L.E. *et al.* (2001) *The Century of Space Science*, 1325-1376. Kluwer Academic Publishers. [14] Boyet M. and Carlson R.W. (2005) *Science 309*, 576-580. [15] Neal C.R. and Kramer G.Y. (2006) *Am. Mineral.*, **91**, 1521-1535.