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

Introduction:
Lunar meteorite Kalahari 009 is a fragmented 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 <119 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 opaques-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 sieved the 74-44 μm fraction into 149-74 μm size fractions.

Sm-Nd isotopic results: Fig. 1 shows 147Sm/144Nd and 143Nd/144Nd 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 λ(147Sm)=0.00654 Ga⁻¹ and an initial εNd=+0.83±0.47 relative to the chondritic reservoir (CHUR) of [7] or initial εNd=−0.04±0.47 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 λ(87Rb) 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.

Remote-sensing analyses of TiO₂ 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 = $0.699322 \pm 0.001402$ Ga 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, and thus, no independent age can be obtained from these samples. Because the Plag(r) datum is probably least affected by desert alterations. Therefore, both VLT and AMB basalts could be samples of the cryptomaria.

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 ($\mu$) 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-$\mu$ (~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-$\mu$ (~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 $\varepsilon_{Nd}$ 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 Reservoir (HEDR) value of $\varepsilon_{Nd}$ of the initial $^{147}$Sm/$^{144}$Nd parameter. Recent measurements of Nd isotopes of chondrites suggested the Earth (Moon also?) is non-chondritic in $^{147}$Nd/$^{144}$Nd [14], probably also in $^{147}$Sm/$^{144}$Nd [8, 9]. The HEDR value is ~0.876 higher than the CHUR value [7]. The dotted lines represent time-averaged source $^{147}$Sm/$^{144}$Nd ($\mu$) values for 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 $\mu$ = ~0.21, i.e., a slightly LREE-depleted source, whereas the old Kalahari VLT came from a nearly chondritic Sm/Nd source ($\mu$ = ~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].