Goldschmidt 2000
September 3rd–8th, 2000
Oxford, UK.

Journal of Conference Abstracts
Volume 5(2), 632

Lu-Hf Systematics and the Early Evolution of the Moon

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The origin and chemical evolution of the Moon have been the subjects of intense and multi-disciplinary studies for the past several decades. It is generally believed that the predominant mineralogical and chemical differentiation within the early lunar interior was associated with the lunar magma ocean (LMO), presumably occurred within the first 200 million years after the cessation of the accretion of the Moon. The flotation and separation of relatively less dense plagioclase from the more dense mafic phases were accomplished during the latter portion of the LMO crystallisation. The final fractionation of the LMO resulted in residual liquids, enriched in trace elements (urKREEP). Effectively, the plagioclase rose to the top of the LMO and formed the bulk of the lunar highland crust. High magnesium and alkali rocks in the highlands formed slightly later, probably by serial magmatism. Lunar mantle underwent further chemical and gravitational differentiation and was later sampled by mare basalts that exhibit significant chemical diversities.

Although our understanding of the origin and evolution of the Moon has progressed significantly, many questions, i.e., the timing, duration, and extend of the LMO, remain. This is due not only to the lack of new samples, but more importantly to the limited sensitivity of the instrumentation employed. For example, compared to Rb-Sr and Sm-Nd isotope systems, Lu-Hf system is more sensitive to mineralogical variations and is thus better suited to study the evolution of lunar mantle. However, Lu-Hf data are scarce and are exclusively for mare basalts due to analytical difficulties in the past. Here we present preliminary MC-ICP-MS Lu-Hf results for a suite of lunar samples, including the first Lu-Hf data for lunar highland rocks, lunar volcanic glasses (LVG), and KREEP basalts, in an attempt to better constrain the origin and chemical evolution of the Moon.

Samples of over 20 lunar rocks have been analysed, including a suite of mare basalts, a lunar meteorite, two KREEP basalts, green and orange volcanic glasses, and a suite of highland rocks. Preliminary results indicate that both major highland rock types (anorthosites and Mg-suite rocks) yield positive ε_{Hfi} relative to the chondritic evolution curve for Hf, suggesting that these highland rocks originated from a source that had already been differentiated. Similar results have also been documented by Sm-Nd system for anorthosites (Borg et al., 1999). Our results, albeit in an early stage, would appear to have profound implications for the nature, duration, and extend of the LMO.

All the mare basalts studied here exhibit radiogenic ε_{Hfi} (+9 to +52), consistent with previous studies (Unruh et al., 1984). The only exception is the high-Al basalt 14053 (ε_{Hfi} = -1.3), which is from the earliest stages of mare volcanism and may have a significantly different origin, compared to the post-4 Ga mare volcanisms. Both KREEP basalts, 15382 and 15386, exhibit near-chondritic ε_{Hfi} values (+1.6 and +3.0), and near-chondritic ε_{Ndi}. It has been suggested from the trace-element data that mare basalt magma may have assimilated certain KREEP components, a concept entirely consistent with the Hf data. In fact, both KREEP basalts lie near the end-member of the extended high-Ti and low-Ti basalt trends in the Nd-Hf isotopic plot of Beard et al. (1998).

The A-15 green and A-17 orange glasses exhibit ε_{Hfi} = +7 and +13, respectively, similar to those of high-Ti basalts. These volcanic glasses are speculated to have originated from the deep lunar interior, equivalent to the depth of the source of the high-Ti basalts. In fact, all high-Ti basalts lie on a mixing trend between lunar volcanic glass (LVG) and KREEP basalts on a Nd-Hf diagram seems to suggest that the high-Ti magma may have shared the same sources as to the LVGs while assimilating urKREEP components during its ascension from depth.

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