RADIOGENIC ISOTOPES IN LUNAR BASALTS. A. A. Nemchin[1], R. Merle[2], M.J. Whitehouse[3], J.F. Snape[4], J.N. Connelly[5] and M. Bizzarro[5], [1]School of Earth and Planetary Sciences, Curtin University, Perth, GPO Box U1987, WA 6845, Australia, [2]Department of Earth Sciences, Natural Resources and Sustainable Development, Uppsala University, Villavägen 16, 75236 Uppsala, Sweden, [3]Department of Geosciences, Swedish Museum of Natural History, SE-104 05 Stockholm, Sweden, [4]Department of Earth and Environmental Sciences, The University of Manchester, Manchester, M13 9PL, UK, [5] Centre for Star and Planet Formation, GLOBE Institute, University of Copenhagen, Øster Voldgade, 5-7, DK-1350 Copenhagen, Denmark,

Introduction: Basalts are products of melting in planetary mantles and, as such, provide means to investigate chemical composition and variability in planetary interiors. In particular, studies of radiogenic isotopes in basalt samples allow evaluation of time related changes in parent to daughter element ratios in basalt mantle sources to be made and differentiation processes leading to mantles heterogeneities to be assessed. Work on terrestrial basalts resulted in establishing a distinct sub-field in geochemistry referred to as chemical or sometimes isotope geodynamics, which identifies diverse reservoirs in Earth's mantle and attempts to describe their formation and interaction, linking chemistry to the plate tectonic models [1]. On the Moon, similar constraints are still in their infancy. The proposed main reservoirs explaining the major chemical types of lunar basalts (low- and high-Ti as well as KREEP, for high K, REE and P) are anticipated from the Lunar Magma Ocean (LMO) model, but their dynamic interaction leading to formation of the basalts with distinct chemical characteristics is poorly understood. The aim of this presentation is to assess isotope data currently available for lunar basalts, identify possible conclusions that can be made on the basis of this data and define further analytical steps that can be made to improve our understanding of lunar mantle stratigraphy and processes that led to the formation of basaltic rocks on the Moon.

Pb, Sr and Nd isotopes: Development of the SIMS (secondary ion mass spectrometry) approach to analyze Pb isotope compositions in lunar basalts during the last decade [2] helped to deal with the problem of terrestrial contamination of the samples, which complicated previous studies of this system in lunar samples. While not utilizing full U-Pb analytical protocols, it allows us to improve accuracy of obtained ages of samples using the Pb-Pb isochron method. In addition, it permits estimation of Pb initial isotope compositions of the samples, which reflect U-Pb ratios in their sources at the time of samples formation.

Compiling available initial Pb isotope compositions indicates the existence of systematic trends shown separately by both high- and low-Ti basalts on $^{207}Pb/^{206}Pb$ vs. $^{204}Pb/^{206}Pb$ diagram (Fig.1). These trends cannot be explained by time related ingrowth of radiogenic Pb in two separate (high- and low-Ti) mantle reservoirs but can be interpreted as two component mixtures where each sample reflects mixing of material from isotopically primitive high- and low-Ti sources in the mantle with an enriched component (probably KREEP). In addition to Apollo 12 and 15 samples, the trend for low-Ti basalts can potentially also include a group of ~3.0 Ga meteorites (such as NWA 773) and the YAMM meteorites (e.g., Asuka 881757). The latter are characterized by relatively low μ- values ($^{238}U/^{204}Pb$). Plotting these datasets on a $^{204}Pb/^{206}Pb$ vs. Age diagram (Fig. 1) indicates that the proportion of enriched component progressively increases in younger basalts (both high- and low-Ti), which is a primary feature of basaltic melts and not related to their differentiation after formation.

Sr isotopes appear to mimic the behavior of Pb system, with younger basalts generally showing more radiogenic initial Sr values in both high- and low-Ti basalts (Fig. 1). However, Nd initial isotope compositions indicate a more complex pattern that cannot be fully explained by a simple two component mixing. This is particularly visible in the group of low-Ti basalts, though there is a significant scatter of initial Nd compositions in the currently available data set, even for multiple independent estimates obtained for the same sample. For example, in older Apollo 15 basalts Pb isotopes suggest a lower proportion of enriched component as compared to ilmenite rich younger Apollo 12 basalts, whereas Nd systematics suggest opposite relationships (Fig. 1).

Discussion:

There are several conclusions or directions for further investigation that can be made/defined from the existing set of isotope data. Pb and Sr isotope systems appear to support the existence of two relatively primitive reservoirs in the lunar mantle as well as separate enriched (KREEP) reservoir, all presumably formed as a result of the original LMO differentiation. Individual samples of two main types of mare basalts can be explained then by various proportions of mixing of material derived from either of two primitive sources with KREEP. The KREEP mixing was invoked before to explain observed variations in chemistry and isotope systems of different basalts from several landing sites [e.g., 3] with several mechanisms

proposed to accommodate this KREEP component contribution. These mechanisms can be roughly combined within three different scenarios with different means of bringing primitive materials and KREEP together: (a) assimilation of KREEP by basalt melt either during assent of basaltic magma or at the surface of the Moon, (b) melt trapped during formation of the source from LMO, and (c) mixing of KREEP material into the mare basalt sources during mantle overturn. None of these scenarios, however, explain the apparent increase of the KREEP mixing proportion in younger basalts. There is no justification for an absence of larger volumes of KREEP mixing during earlier melting of the lunar mantle. The presence of correlated changes in mixing proportions and age suggests possible time related increase in the amount of enriched materials within the deeper mantle where melting of high- and low-Ti sources takes place. This gradual increase implies the possibility of sustained mantle convection that gradually eroded KREEP rich layer formed by LMO crystallization and originally located under the lunar crust gradually delivering enriched materials into the deeper parts of the mantle.

It is possible that the low-μ (YAMM) meteorites represent most primitive low-Ti reservoir, but they can also form in a separate source not related to LMO crystallization, which would imply that LMO is not global and restricted to the near side of the Moon. It is also unclear whether basalt sampled by the Chang'e 5 mission represent a different source or how this relates to LMO crystallization. Recent studies suggested that KREEP is not incorporated into Chang'e basalt melt [4]. However, all isotope systems indicate the possibility of KREEP mixing into this melt comparable to the level observed in Apollo basalts.

The dichotomy between Pb and Nd initial compositions remains unexplained, but it indicates that early differentiation processes on the Moon could be more complex than envisioned under the current LMO model. As a result, recognition of three main reservoirs corresponding to the major types of lunar basalts does not reflect all the variability in the lunar mantle. It is possible that further clues to the reasons for this variability could be found in different element partitioning for three isotope systems, where parent isotopes for U-Pb and Rb-Sr systems are both strongly incompatible, while daughter isotopes are accumulated in plagioclase. This contrasts with Sm (parent isotope) being more compatible than Nd (daughter isotope).

Addressing these issues will improve our understanding of early differentiation of the Moon, stratification of lunar mantle and formation of lunar basalts.

References:
[1] Zindler A. and Hart S. (1986) *Ann Rev Earth Planet Sci*, *14*, 493-571. [2] Snape J.F. et al. (2016) *EPSL, 451,* 149-158. [3] Snyder G.A. et al. (1997) *GCA, 61*, 2731-2747. [4] Tian, H.-C. et al. (2021) *Nature 237*, 59–63
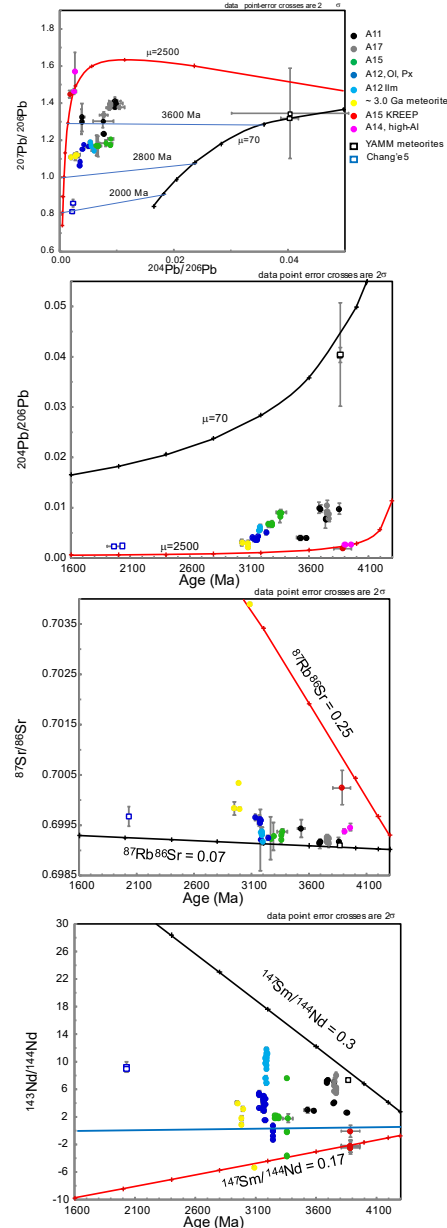
Figure 1: Initial compositions of lunar basalts; red curves and lines represent enriched (KREEP-like) reservoir; black curves and lines model a primitive reservoir). Values for parent- daughter ratios selected to illustrate possibility of two component mixing and do not represent accurate estimates for primitive and enriched reservoirs (all data are compiled from multiple publications that are difficult to acknowledge in an abstract reference list)