

**TRACING THE GENETICS OF LUNAR IMPACTORS.** K. R. Bermingham<sup>1</sup> and R. J. Walker<sup>1</sup>, <sup>1</sup>Department of Geology, University of Maryland, College Park, Maryland, 20742, USA ([kberming@umd.edu](mailto:kberming@umd.edu)).

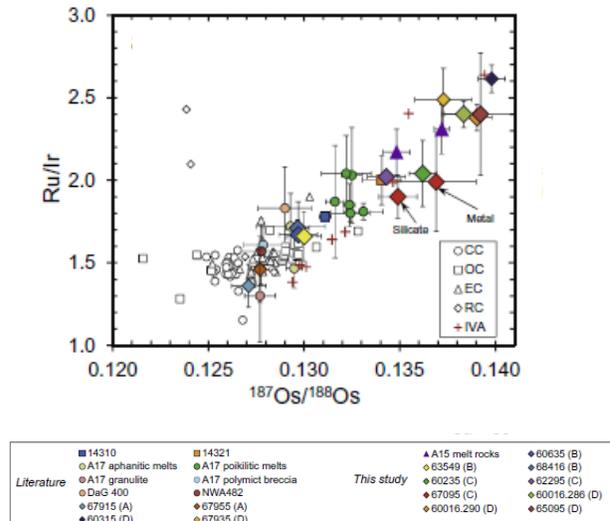
**Introduction:** The lunar surface has been completely reworked by impact events. The putative period during which most of this activity occurred, often termed the *late heavy bombardment* (LHB), is generally considered to have been from ~4.1 to ~3.8 Ga [1-3]. Based on chemical studies of lunar material and dynamical modelling, it is hypothesized that as much as 10 % of the total mass of late accreted material ( $\leq 0.05$  wt% accretion) was added to the Earth-Moon system during this time [4-6].

The composition of material added during the LHB remains debated. Identifying the provenance of lunar impactor material, however, would provide important constraints on what constituted these final building blocks of the Earth-Moon system, and perhaps also pinpoint how critical quantities of hydrous- and organic-rich material were added to Earth.

The traditional approach used to identify lunar impactors involves contrasting the chemical composition (e.g., abundances of highly siderophile elements, HSE) of lunar impact melt breccias (LIMB) and/or lunar soils with those of meteorites and terrestrial samples. This technique is viable because the abundances of the endogenous HSE present in lunar rocks are low, thus, the HSE signatures of LIMB and lunar soils are commonly strongly biased towards those of impactors. For example, pristine ferroan anorthosites and magnesian suite rocks have Ru concentrations averaging  $6.8 \pm 2.7$  ppt and  $58 \pm 53$  ppt, respectively [7]. Possible impactors (e.g., chondrites or irons), have much higher HSE concentrations with Ru concentrations typically ranging from 400 to 1000 ppb [8].

Studies of Apollo impact melt breccias have pointed to a predominately asteroidal reservoir for material added during the lunar cataclysm [9-13]. For example, Re-Os systematics and HSE abundances of LIMB suggest that impactors may have included EH-chondrites, ordinary chondrites, iron meteorites, evolved metal separated from a fractionated planetesimal core, or (as yet) unsampled material (**Fig. 1**, [7,9-15]). This concurs with dynamical modelling predictions, which propose either asteroidal or cometary origins of LHB impactor material [4,16].

A more exacting approach to identifying the composition of lunar impactors, however, is via *isotope genetic testing*. This approach has developed following the discovery of non-mass-dependent isotope anomalies in meteorites and their components [18-21] and the

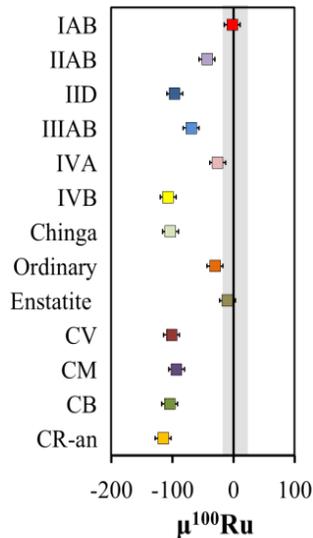


**Fig. 1.** The average  $^{187}\text{Os}/^{188}\text{Os}$  vs.  $\text{Ru}/\text{Ir}$  for the impactor components incorporated in LIMB compared to compositions of chondrites (gray symbols), and IVA iron meteorites (red crosses). All lunar data appear to plot along a linear trend ranging from a composition similar to ordinary chondrites, to an endmember with compositions higher than that of known chondrites (e.g., irons). Figure from [12], lunar data from [9-12], meteorite data from [8,15,17,18].

advent of high precision isotope analytical techniques ( $<10$  ppm 2SD). Non-mass-dependent isotope variations in meteorites (here termed *nucleosynthetic isotope anomalies*) originate from the heterogeneous distribution of nucleosynthetic material throughout the solar nebula (where isotope variation refers to isotope ratios that differ from the average terrestrial composition). The exact process(es) by which these isotope anomalies developed remain debated, but may include thermal or physical sorting mechanisms of host phases in the solar nebula or incomplete homogenization of these host phases in the solar nebula [22,23]. Assuming that such isotopically anomalous material comprised part of the impactor population of the LHB, we can use these isotope systems to genetically fingerprint the discrete accreting materials. Evidence that such genetically diverse material formed part of the LHB impactor population comes from chemical studies of LIMB and lunar soils (e.g., **Fig. 1**).

We aim to constrain the genetics of lunar impactors by contrasting Ru isotope signatures of lunar soils and LIMB with those of different meteorites. The HSE Ru

isotope system is well suited to this study given that there are very low endogenous Ru concentrations in lunar materials coupled with far higher concentrations in potential impactor material [7,8]. And, importantly, well-resolved nucleosynthetic Ru isotope anomalies have been identified in a number of meteorites (Fig. 2, [20,21,24]). These isotope anomalies have been interpreted to reflect a deficit in s-process material in the regions of the solar nebula where planetesimal accretion was taking place.



**Fig. 2.** Average  $\mu^{100}\text{Ru}/^{101}\text{Ru}$  ratios isotope composition for meteorite groups. Units are in  $\mu^{100}\text{Ru}$ , where  $\mu^{100}\text{Ru}$  is the deviation in ppm of  $^{100}\text{Ru}/^{101}\text{Ru}$  relative to zero. The external precision for repeated analyses of a standard reference material is  $^{100}\text{Ru}/^{101}\text{Ru} \pm 13$  ppm ( $2\sigma$ ) and is indicated by the grey field. Data from [21,24].

**Methods:** Ru isotope compositions will be measured using a Thermo Fisher Triton Plus thermal ionization mass spectrometry operated in negative mode at the Department of Geology, University of Maryland. Using newly refined analytical methods [25], replicate analyses of an Alfa Aesar Ru standard indicate an external precision of  $\pm 6$  ppm ( $2\sigma$  SD) for  $^{100}\text{Ru}/^{101}\text{Ru}$  ( $n=18$ ) for  $\sim 1000$  ng Ru per analysis. Data are corrected for instrumental mass fractionation using the exponential law and  $^{99}\text{Ru}/^{101}\text{Ru}$  as the normalizing ratio. The lunar soils and impact melt breccias that we plan to analyze, however, have far lower Ru concentrations ( $\sim 20$  ng Ru per sample). Preliminary work indicates that we can achieve  $^{100}\text{Ru}/^{101}\text{Ru} \pm 100$  ppm ( $2\sigma$  SD) for  $\sim 20$  ng Ru loads. Given the small signal sizes achieved during this type of analysis, we are currently investigating the use of  $10^{12} \Omega$  resistors in all amplifiers to reduce the signal:noise ratio during analysis of  $<10$  mV signals. It is anticipated that this will improve the current analytical precision enabling us to reach  $^{100}\text{Ru}/^{101}\text{Ru} \pm 30$  ppm ( $2\sigma$  SD). Optimism for this approach is based on our recent success of using these resistors to measure *in-situ* oxygen compositions during analysis of high abundance Ru loads [25].

We are currently processing  $\sim 2$  g of a lunar impact melt breccia (76215.46, a well characterized sample with HSE abundance data and Re-Os systematics documented [11]).

Analytical methods are detailed in [25]. Briefly,  $\sim 2$  g of LIMB 76215.46 was requested from the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM). The sample was gently broken apart in an agate mortar and pestle, but not finely ground in order to prevent smearing of metal within the mortar [following 9,11,12]. The sample was digested in inverse aqua regia for 2 days at  $210^\circ\text{C}$ . Complete digestion was not achieved, however, this is not considered problematic because the metal phases in which the Ru is largely sited were dissolved. After centrifugation, the sample was processed through cation exchange columns for the isolation of HSE. Ultra-pure Ru was obtained after microdistillation of the HSE fraction.

**References:** [1] Turner G. et al. (1973) *Proc. 4<sup>th</sup> Lunar Sci. Conf.*, 1889-1914. [2] Tera F. et al. (1974) *Earth Planet. Sci. Lett.*, 22, 1-21. [3] Kring and Cohen (2002) *J. Geophys. Res.*, 107(E2). [4] Morbidelli et al. (2012) *Earth Planet. Sci. Lett.* 355, 144-151. [5] Marchi et al. (2014) *Nature* 511, 578-582. [6] Morgan et al. (2001) *Met. Planet. Sci.* 36, 1257-1275. [7] Day J. M. et al. (2010) *Earth Planet. Sci. Lett.* 289, 595-605. [8] Horan M. F. et al. (2003) *Chem. Geol.* 196, 5-20. [9] Puchtel I. S. et al. (2008) *Geochim. Cosmochim. Acta.*, 72, 3022-3042. [10] Fischer-Gödde M. & Becker H. (2012) *Geochim. Cosmochim. Acta.*, 77, 135-156. [11] Sharp M. et al. (2014) *Geochim. Cosmochim. Acta.*, 131, 62-80 [12] Liu J. et al. (2015) *Geochim. Cosmochim. Acta.*, 155, 122-153. [13] Norman M. D. et al. (2002) *Earth Planet. Sci. Lett.* 202, 217-228. [14] Chen J. et al. (2002) *LPSC XXXIII*, Abstract #1818. [15] Walker, (2004) *Earth Planet. Sci. Lett.* 224, 399-413. [16] Hartmann W.K. and Davies D.R. (1975) *Icarus*, 24, 504-515. [17] Fischer-Gödde et al. (2010) *Geochim. Cosmochim. Acta.*, 74, 356-379 [18] McCoy T.J. et al. (2011) *Geochim. Cosmochim. Acta.*, 75, 6821-6843. [19] Zinner et al., 2008. [20] Chen J. et al. (2010) *Geochim. Cosmochim. Acta.*, 74, 3851-3862. [21] Fischer-Gödde et al. (2015) *Geochim. Cosmochim. Acta.*, 168, 151-171. [22] Trinquier et al., 2009, *Science* 324, 374-379. [23] Carlson et al., 2007, *Science*, 316, 1175-1178. [24] Bermingham K.R. et al. (2015) *LPSC XLVI*, Abstract #1588. [25] Bermingham K.R. et al. (in review) *IJMS*.