



Highly Siderophile Element Constraints on Accretion and Differentiation of the Earth-Moon System

James M. D. Day, *et al.*
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is reduced and the filling is increased. In the $N = 2$ to $N = 5$ Landau levels, the FQHE is replaced by a strong spontaneous resistive anisotropy aligned with principal in-plane crystal axes, even though the crystal symmetry shows no evidence of orthorhombicity. The anisotropy exists even for fields perpendicular to the plane of the device (presumably because of some symmetry-breaking gradients introduced during device fabrication) but can be rotated by 90° by applying a modest in-plane field. Just as in the present observations on $\text{Sr}_3\text{Ru}_2\text{O}_7$, the GaAs data have strong temperature and purity dependencies, and the easy direction lies perpendicular to an in-plane field applied along one of the two relevant crystalline principal axes.

The phenomenological similarity between the GaAs and $\text{Sr}_3\text{Ru}_2\text{O}_7$ results suggests a common origin for the observations. The disorder dependence gives an important clue, because strong sensitivity to elastic scattering is the signature of a state that is anisotropic in \mathbf{k} -space, as is well known in unconventional superconductivity (26). The challenge is how to reconcile what are, apparently, large differences in the starting physical situations. To promote self-organization of a correlated electron system, one must tune the ratio of a potential energy term often summarized by the parameter U (the Coulomb repulsion, which tends to localize) to the kinetic energy, often denoted by W , which tends to delocalize. If this is done “chemically,” by forming new compounds, the change in the U/W ratio is strongly linked to a change to the electron-lattice coupling, because increasing U and decreasing W also involves increasing the strength of the periodic potential. In the GaAs devices, it is possible to increase the U/W ratio by quenching the kinetic energy by going to very low Landau levels. This leads to a relatively high effective correlation strength without an increase in the effective strength of the periodic potential. In $\text{Sr}_3\text{Ru}_2\text{O}_7$, similar basic physics is taking place but with a different kind of tuning. It is intrinsically a strongly correlated material, so the starting periodic potential is much larger than in GaAs. However, the existence of an underlying metamagnetic quantum critical point makes the quasiparticle mass m^* diverge on the approach to criticality (15, 27). This mass divergence is another route to increasing U/W without increasing the strength of the periodic potential, hence freeing the correlated electron fluid from its rigid link to the underlying lattice.

We have shown that in highly restricted parts of its phase diagram, in proximity to metamagnetic quantum critical points, the electron fluid in $\text{Sr}_3\text{Ru}_2\text{O}_7$ develops a strong resistive anisotropy, whose hard and easy axes can be interchanged by the application of modest in-plane magnetic fields. The data are consistent with the formation of a nematic state with broken rotational symmetry. Intriguingly, a correlated electron nematic arising from a Pomeranchuk-like Fermi surface distortion (4, 28–36) possesses two of the key features that are present in our data and those from GaAs, namely the \mathbf{k} -space anisotropy that would give a strong disorder dependence and the

possibility of anisotropic transport, intrinsic or through domain formation (37). Whatever the detailed microscopic origin (38), our data suggest that nematic behavior is a feature of ultraclean low-dimensional correlated electron systems in which the bandwidth can be reduced independently of changes to the strength of the periodic potential.

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information on the temperature dependence of the formation of the nematic state. It should not, however, be overinterpreted. As a macroscopic parameter, it suffers from the same flaws as the magnetization in a ferromagnet; in addition, we cannot rule out the possibility of multiband effects in which electrons in bands based on only one species of underlying orbitals participate in the nematic ordering.

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38. Nematic behavior could also result from a wide variety of spin and charge textures that have not, so far, been examined theoretically in the context of itinerant metamagnetism.
39. We thank L. Balents, E. Fradkin, A. G. Green, C. A. Hooley, K. Y. Kee, Y. B. Kim, S. A. Kivelson, and B. D. Simons for a number of insightful discussions, V. V. Sikolenko and K. Prokes for help and advice, and the UK EPSRC, Royal Society, and Leverhulme Trust for financial support.

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Highly Siderophile Element Constraints on Accretion and Differentiation of the Earth-Moon System

James M. D. Day,^{1*} D. Graham Pearson,² Lawrence A. Taylor¹

A new combined rhenium-osmium- and platinum-group element data set for basalts from the Moon establishes that the basalts have uniformly low abundances of highly siderophile elements. The data set indicates a lunar mantle with long-term, chondritic, highly siderophile element ratios, but with absolute abundances that are over 20 times lower than those in Earth’s mantle. The results are consistent with silicate-metal equilibrium during a giant impact and core formation in both bodies, followed by post-core-formation late accretion that replenished their mantles with highly siderophile elements. The lunar mantle experienced late accretion that was similar in composition to that of Earth but volumetrically less than (~0.02% lunar mass) and terminated earlier than for Earth.

The histories of Earth and the Moon are intrinsically linked, with a catastrophic giant impact considered to be the most likely mode of origin of the Earth-Moon system (1, 2).

After this event, both bodies experienced early [4.53 ± 0.01 gigayear (Gyear)] global-scale differentiation (3, 4), forming metallic cores and silicate mantles and crusts. However, uncertainty exists in

several aspects of these planetary evolution models. For example, the influence of core formation and the relative timing and composition of late-accretion material to the Moon's mantle from bodies striking the surface are poorly constrained (5, 6). This has important consequences for metal-silicate equilibrium (5), the so-called late veneer on Earth (7) and its apparent relation to the rise of life (8), and lunar late heavy bombardment (9).

Highly siderophile elements (HSEs: Re, Au, Ir, Os, Ru, Rh, Pt, and Pd) and the Re-Os isotope system embedded within these elements offer a means to address these problems, because they are effective tracers of the early stages of planetary evolution (10). They are sensitive to metal-silicate equilibria during core formation and to the subsequent addition of primitive, HSE-rich undifferentiated materials to silicate mantles after core segregation. The abundances of HSEs in Earth's mantle ($\sim 0.008 \times C1$ chondrite) are elevated relative to those predicted from metal-silicate equilibrium ($\leq 0.00001 \times C1$ chondrite). Although high-temperature, high-pressure silicate-metal equilibrium can account for depletion of HSEs in planetary mantles, it cannot explain the chondritic proportions of HSEs in Earth. This observation is considered to be primary evidence for late accretion after core formation (6, 7). In contrast, great uncertainty exists regarding lunar-mantle HSE abundances (5). Determining lunar-mantle HSE contents has been problematic because of a lack of direct mantle samples, together with low HSE abundances in mare basalts, melts of the lunar interior, and potential mantle proxies. Severe leaching of pyroclastic glasses, which have experienced meteoritic and magmatic condensate contamination, and analysis of a dunite cumulate point to lower HSE abundances for the Moon's mantle as compared with Earth's, but more substantive data are needed to draw any conclusions (11).

We report precise Os-isotope- and HSE-abundance data (table S1) for five basalts from the Apollo 15 mission, six from Apollo 17, and six lunar basalts of meteoritic origin from LaPaz, Bolivia, that were obtained by using an ultra-low-blank, isotope-dilution digestion technique (12). In contrast to pyroclastic glasses, the selected samples are unaffected by meteoritic contamination (13–15) and hence offer an opportunity for determining the HSE and Os-isotope compositions of the lunar mantle.

A striking feature of the data is that lunar basalts have lower HSE abundances than terrestrial mid-ocean ridge basalts (MORBs) with comparable-to-lower MgO contents (Fig. 1). In some samples, Ir-Pt-group elements (I-PGEs: Os, Ir, and Ru) are fractionated to lower abundances than Pd-PGEs (P-PGEs: Pt and Pd), but others have relatively flat, unfractionated PGE patterns. Fractionation of I-PGE and P-PGE results from extensive partial

melting or crystal/melt separation, in which more compatible I-PGEs remain in the mantle residue or are trapped within early-formed minerals (16, 17). Variations in mare-basalt HSE abundances and PGE patterns can be explained by fractionation of olivine and chromite, as recognized from their major-element compositions (18, 19). LaPaz basalts have large I-PGE and P-PGE fractionations relative to Apollo basalts (Fig. 1), consistent with their incompatible-element-enriched and -fractionated nature (13). Measured $^{187}\text{Os}/^{188}\text{Os}$ compositions for Apollo 15 and 17 basalts (0.1265 to 0.1729) are nearly chondritic as compared with the LaPaz basalts (0.1697 to 0.4628), in agreement with a preliminary study of two of the basalts (20). Initial $^{187}\text{Os}/^{188}\text{Os}$ ratios range from within 5% of chondritic values to values far below the solar system initial composition.

Another remarkable attribute of the data set is the ubiquitously low Re contents of lunar basalts, which were previously ascribed to low oxygen fugacity ($f\text{O}_2$) in the lunar mantle, affecting HSE partitioning during melting (20). However, postulated redox effects on Re compatibility during melting have not been experimentally verified and assume similar S contents for the lunar and terrestrial mantles (20). Studies of mare-basalt olivine melt inclusions indicate that the lunar mantle has S contents that are two to three times lower than in the terrestrial mantle, such that $f\text{S}$ may be more

dominant than $f\text{O}_2$ in controlling HSE partitioning (21). Our data demonstrate that Pt and Pd are also anomalously low in the lunar mantle, as are Ir, Ru, and Os. PGEs are unlikely to be as redox-sensitive as Re, and hence, our view is that $f\text{O}_2$ cannot be the dominant control on low lunar HSE abundances, even if it cannot be ruled out for controlling Re.

Samples with low initial $^{187}\text{Os}/^{188}\text{Os}$ have low MgO and Os abundances [<10 parts per trillion (ppt)], with measured $^{187}\text{Os}/^{188}\text{Os}$ being the most divergent from chondrites. PGE patterns for these basalts show the greatest interelement fractionation, with $(\text{Pd}/\text{Ir})_n$ and $(\text{Os}/\text{Ir})_n$ (where n denotes the chondrite-normalized ratio) deviating substantially from the chondritic value of 1. Re enrichments with $(\text{Re}/\text{Os})_n > 1$ are also evident. The very low Re and Os abundances in these samples make them extremely susceptible to minor Re addition or Os loss [supporting online material (SOM) text]. Their initial $^{187}\text{Os}/^{188}\text{Os}$ ratios are too low for their sources to have interacted with a component with low time-integrated Re/Os before magmatism. Although we are not able to conclusively determine whether Re addition or Os loss is responsible, these basalts have obviously experienced a multistage evolution. We classified these basalts as "disturbed" and did not consider them in constraining the evolution of the lunar mantle.

Mare basalts with generally higher MgO contents have relatively elevated I-PGE contents

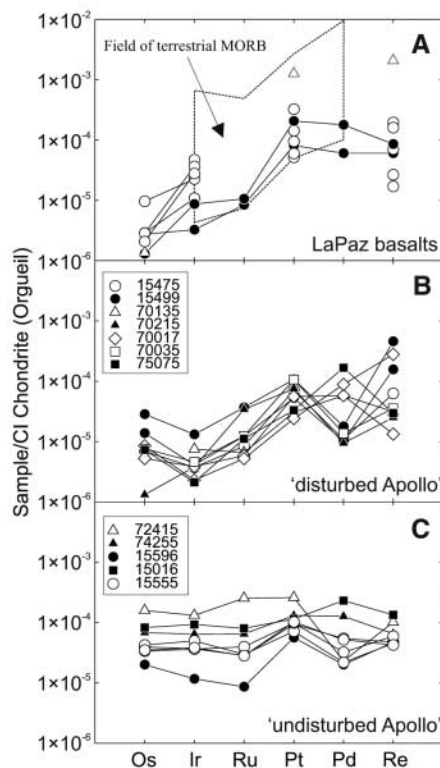


Fig. 1. Chondrite-normalized (Orgueil C1) PGE patterns for lunar mare basalts versus terrestrial MORBs. (A) LaPaz basalts, including CT (open circles), HPA digestions (black circles), and the fusion crust sample no. LAP 02224, 17 (open triangles). (B and C) Apollo 17 (high-Ti) and Apollo 15 (low-Ti) disturbed (B) and undisturbed (C) basalts (SOM text).

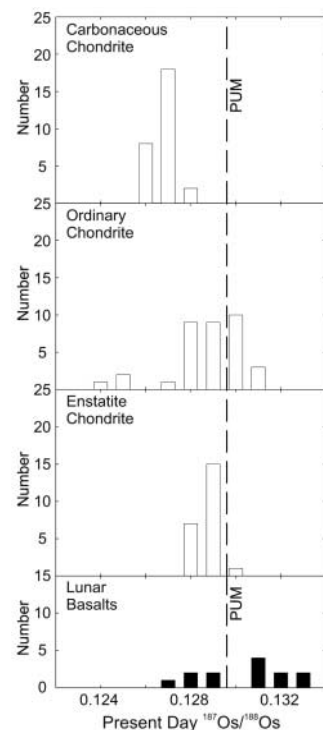


Fig. 2. Histogram range of the measured $^{187}\text{Os}/^{188}\text{Os}$ values for chondrites versus lunar basalts. The lowest measured $^{187}\text{Os}/^{188}\text{Os}$ values for mare basalts lie in the range of chondritic compositions, and the primitive upper mantle (PUM) composition is derived from terrestrial-mantle peridotites (SOM text). Number indicates the number of samples analyzed.

¹Department of Earth and Planetary Science, University of Tennessee, Knoxville, TN 37996, USA. ²Department of Earth Sciences, University of Durham, Durham, DH1 3LE, UK.

*To whom correspondence should be addressed. E-mail: jday13@utk.edu

(Os >10 ppt), unfractionated PGE patterns with $(\text{Pd}/\text{Ir})_n$ and $(\text{Os}/\text{Ir})_n$ close to 1, and initial Os isotopic compositions that are within 5% of chondritic values (Figs. 1 and 2 and table S1). We classified these samples as “undisturbed” (74255, 15016, 15555, and 15596) and used them to consider Os-isotope and HSE compositions of lunar-mantle source regions. Undisturbed samples have origins consistent with mantle-derived melts that have experienced olivine and spinel accumulation (19, 20). The effect of this accumulation would be to increase I-PGE abundances (17), thereby flattening PGE patterns. The enhanced I-PGE abundances result in estimates of the probable conservative maxima of lunar-mantle HSE abundances. Near-chondritic Os-isotope ratios of undisturbed basalts indicate derivation from a source that experienced long-term chondritic evolution of Re/Os (and by inference, HSE ratios), which maintained this character through the eruptive duration of the basalts, until at least 1 Gyear after Moon formation.

It is unlikely that HSE ratios would remain close to chondritic values if they were affected by contamination from the lunar crust during the eruption of the basalts (SOM text). The selected samples have been well characterized and show no evidence of crustal or meteoritic contamination (14, 15, 18, 19). Therefore, unfractionated PGE patterns among undisturbed mare basalts probably result from relatively small degrees of melting (<<15%, SOM text), plus minor olivine and chromite accumulation.

Extrapolations to mantle abundances from basaltic compositions are complicated by uncertainties in HSE mantle-melt partitioning (5). An empirical approach is to compare mantle-melt products from the Moon with those from Earth, assuming that relative offsets reflect the same magnitude of offset in mantle HSE contents (11). This comparison is most robustly done with I-PGEs that are least affected by degassing effects on Earth (22). HSE abundances were estimated by regressing lunar and terrestrial PGE data to an assumed fertile mantle MgO composition, accounting for the lower MgO

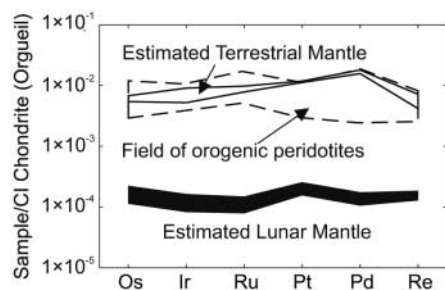


Fig. 3. Estimated lunar- and terrestrial-mantle PGE abundances and patterns versus terrestrial orogenic peridotites. Estimates for mantle compositions were made by regressing Os, Ir, Ru, Pt, Pd, and Re versus MgO data (SOM text and fig. S2). Both lunar and terrestrial mantles have chondritic relative abundances of HSEs, but the Moon’s mantle possesses abundances nearly two orders of magnitude less than those of Earth. Calculated concentrations for the lunar mantle are ~0.2 ng/g Pt; 0.1 ng/g Os, Ir, Ru, and Pd; and 0.01 ng/g Re; ~0.0002 × C1 chondrite.

of the lunar mantle. Results yield an estimated terrestrial-mantle composition with nearly chondritic relative abundances (~0.008 × C1 chondrite) and a PGE pattern similar to that of fertile orogenic peridotites (Fig. 3). Regressed data for undisturbed lunar basalts also generate broadly chondritic relative abundances of HSEs, but with all HSE abundances 20 to 40 times lower than terrestrial-mantle estimates (~0.0002 × C1 chondrite, Fig. 3).

Three key observations that place important constraints on lunar evolution were predicted from our data set: (i) low HSE abundances, (ii) chondritic HSE proportions, and (iii) the long-term chondritic Os-isotopic composition of the Moon’s mantle. Two of these characteristics [(ii) and (iii)] are also shared with Earth and point to similar processes being involved in the formation and evolution of Earth and the Moon. A two-stage evolution is required to explain these observations.

Abundances of HSEs were initially lowered in the lunar and terrestrial silicate mantles by metal-silicate partitioning. For both Earth and the Moon, scavenging of HSEs could have occurred through two processes. HSE-depleted mantles may have been inherited during the giant impact, where models predict that nearly all core material for both colliding bodies would have been sequestered into Earth (1, 2). Alternatively, the segregation of cores during planetary differentiation would strip HSEs from silicate mantles. Metal-silicate equilibrium would fractionate HSE ratios, in particular, Re from Os; therefore, a second stage is required to replenish HSEs back to chondritic-relative proportions to ensure a chondritic Os-isotopic evolution for the lunar mantle.

For Earth, post-core-formation accretion of ~0.4% of the mantle mass is thought to have occurred, re-enriching the upper mantle in HSEs by effective mixing of material during mantle convection (6). The observed depletion in lunar-mantle HSEs indicates that the late accretion component was much less important for the Moon. We calculated that the addition of ~0.02% (1.5×10^{19} kg) of the Moon’s mass by accretion of chondritic material would restore chondritic Re/Os and account for the inferred lunar-mantle HSE composition. This is equivalent to an Earth/Moon mass flux ratio of ~2700, which is considerably greater than the ratio of 30 that was estimated from the gravitational-attraction potential of the two bodies (6). Because the lunar cratering record indicates substantial continued impacts after crust formation, we suggest that the thick, ancient >4.4-Gyear (23) lunar crust played a key role in isolating the lunar mantle early in the late accretion phase of lunar evolution, explaining its limited HSE re-enrichment. The mixing and homogenization of any meteoritic post-core-formation HSE inventory to re-create a chondritic mantle for Re-Os isotopes probably occurred in the ~0.1-Gyear period between the inception of lunar differentiation [4.53 ± 0.01 Gyear (3)] and the stabilization of the lunar crust (23). This model, which explains the abundances and chondritic ratios of HSEs in lunar basalts, agrees with other physical and dynamical

constraints on the formation and evolution of the Moon. Mare-basalt HSE data are, therefore, consistent with the giant impact and magma-ocean differentiation models for the Moon followed by prolonged, higher-volume late accretion that was responsible for elevated HSE abundances in Earth’s mantle relative to the Moon.

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- Samples were spiked with a multi-element tracer followed by Carius-tube (CT) or high-pressure–asher (HPA) digestion and solvent extraction for Os and anion exchange column chemistry for Ir, Ru, Pt, Pd, and Re. Long-term $^{187}\text{Os}/^{188}\text{Os}$ reproducibility using the University of Maryland, College Park, standard was 2.7 per mil for standard load sizes of 1.8 to 175 pg/g measured during the course of this study (0.11387 ± 0.00031 , 2σ , $n = 17$, where n is the number of standards analyzed). Blanks for the CT method had the following element concentrations: 0.37 ± 0.05 pg/g [Os], 8 ± 1 pg/g [Re], 2.2 ± 0.1 pg/g [Ir], and 100 ± 10 pg/g [Pt]; $^{187}\text{Os}/^{188}\text{Os} = 0.1577 \pm 0.0011$. Blanks for the HPA method had the following element concentrations: 0.067 ± 9 pg/g [Os], 0.79 ± 0.08 pg/g [Re], 0.9 ± 1.0 pg/g [Ir], 0.82 ± 0.07 pg/g [Ru], 3.3 ± 2.3 pg/g [Pt], and 9.4 ± 9.0 pg/g [Pd]; $^{187}\text{Os}/^{188}\text{Os} = 0.290 \pm 0.007$. Materials and methods are available as supporting material on Science Online.
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Materials and Methods

SOM Text

Figs. S1 and S2

Table S1

References

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ERRATUM

Post date 2 March 2007

Reports: “Highly siderophile element constraints on accretion and differentiation of the Earth-Moon system” by J. M. D. Day *et al.* (12 Jan. 2007, p. 217). In the first sentence of the second full paragraph on page 218, LaPaz, Bolivia, was incorrectly named as the location of meteoritic samples. The corrected sentence should read, “We report precise Os-isotope– and HSE-abundance data (table S1) for five basalts from the Apollo 15 mission, six from Apollo 17, and six lunar basalts of meteoritic origin from LaPaz Icefield, Antarctica, that were obtained by using an ultra-low–blank, isotope-dilution digestion technique (12).”