CAN DEFORMATION INDUCED CORE-MANTLE INTERACTION ACCOUNT FOR THE “LATE VENEER”? T. Rushmer¹, N. Petford², and M. Humayun³, ¹Dept. of Geology, University of Vermont, Burlington, VT 05405 (Tracy.Rushmer@uvm.edu), ²Center for Earth and Environmental Science Research, Kingston University, Kingston-Upon-Thames, UK, ³National High Magnetic Field Laboratory and Dept. of Geological Sciences, Florida State University, Tallahassee, FL 32310, USA.

Introduction: Analyses of representative fertile terrestrial mantle have shown relatively high abundances of highly siderophile elements (HSE) and in chondritic relative proportions [1]. The most often cited source for the pattern and abundance of the HSE is a late accretion event after core formation in the last stages of the growing early Earth [2] with the mass estimated to be added to the early mantle suggested to be somewhere between 0.5 to 0.9 wt% of the Earth [3,4]. Alternatively, internal redistribution of metal by either plume activity in the Hadean [5], residual [6] or redox reaction produced metal [7] have all been suggestion to be possible sources for HSE sequestration in the mantle.

Return flow: Recently, work on liquid metal migration and the associated geochemical signatures produced by this process, has been applied to growing planetesimals [8]. The mechanical model for metallic liquid segregation depends critically on impact-generated deformation setting up a fluid dynamical instability at the core mantle-boundary sufficient to locally drive return flow of core melt back into the mantle. The model requirements are thus energy supplied by surface impacts and a suitable reservoir of liquid core metal, previously segregated from silicate mantle. Given that the outer core has an approximately chondritic PGE pattern, we can also consider the possibility of HSE re-mobilization from the outer core to the Earth’s mantle during the late stages of growth as a possible mechanism for HSE enrichment in the mantle. This is called return flow, and unlike the late veneer, is a mostly internally driven enrichment process. Estimations of the mass required to be transported from the outer core to produce observed abundances and proportions of HSE using deformation-induced shear at the core-mantle boundary is explored below.

Methodology: Details of the mechanical model of liquid metal segregation we use are given in [8]. In short, the shear-enhanced dilatancy model uses a granular deformation mechanism and can quantify rates and fluxes of fluid migration during deformation (Fig. 1). Under appropriate rheological conditions, deformation creates strain gradients such that fluids can be transported locally against gravity, thus a more dense fluid can be moved upwards into an overlying layer of lower density material, once a critical strain rate threshold is reached. This threshold for rock with a shear modulus of the order 200-300 GPa is approximately 10¹⁰ s⁻¹.

Fig. 1a: Sketch of dilatancy effect (Reynolds) produced during shear deformation. Shear produces a volume change between granular domains that results in regions of low pressure in sites between domains, which can draw in surrounding fluid.

Fig. 1b. Deformation experiment in a natural H6 chondrite showing shear zones enriched in metal. While the silicate matrix is being deformed and before the rock fails, the pre-failure behavior allows for migration of liquid metal in zones of low pressure.
We can geochemically explore the possibility of siderophile element introduction in the mantle by impact-driven strain gradients at the core-mantle boundary [8]. The Earth’s mantle has a siderophile element pattern where the abundances of the platinum group elements (PGEs: Os, Ir, Ru, Pt and Pd), Re and Au are more depleted than that of any other siderophile elements and even these elements occur in chondritic relative proportions [9]. The mantle abundances of MSE are thought to have resulted from high P-T equilibration at the base of a magma ocean [9, 10]. We suggest the elemental abundances most sensitive to return flow of outer core material are the PGEs, Au and Re. We have calculated the PGE pattern of mantle that has had either 1% or 0.1% outer core admixture, using both undifferentiated (i.e. bulk) core and differentiated outer core, and assuming that the PGE abundances in the silicate mantle were negligible prior to the admixture [8]. From these calculations, return flow of about 0.1-0.2% liquid outer core provides a satisfactory explanation of the upper mantle PGE pattern without the need for invoking a late chondritic veneer [8]. From these calculations, return flow of about 0.1-0.2% liquid outer core (c. 10^{21} kg) provides a satisfactory explanation of the upper mantle PGE pattern without the need for invoking a late chondritic veneer [8]. To further test this idea we need to calculate the mass of core material remobilized during shear deformation events using these and other constraints provided by the literature. This is done briefly below.

Mass flux compared: Estimates of the external mass of core material required to produce the siderophile element abundance characteristic of the ‘late veneer’ (0.5-0.9 wt% of Earth’s mass) or c. 10^{22} kg have been proposed [3,4,11]. Simple calculations show that an equivalent volume of material, spread evenly across the planet, would cover the entire present-day earth surface to a depth of c. 10^3 m. This material then needs to be mixed into the mantle from above and globally homogenized. Assuming an Fe-alloy density of 10^4 kg m^{-3}, the required 10^{21} kg of mass drawn up from the outer core across the CBM by return flow would make a global layer of thickness c. 10^3 m. Suppose the mass flux to fill this internal layer thickness takes place everywhere across the CMB, driven by a modest (surface impact induced) strain rates of 10^{-5} s^{-1}, the corresponding internal mass flux of c. 3 x 10^{18} kg s^{-1} would require << 1 hr to deliver the required mass. This is of course an end-member calculation describing a ‘one hit’ event. If we assume that the flux area corresponds to only 1% of the present-day surface area of the CMB (~ 10^{15} m^2), the required mass can still in principle be delivered in < 1 day. The length of time of loading experienced by the outer core region during surface impacts is currently unknown. Assuming each surface impact excites the CMB region for 1 minute, then several hundred impacts might be needed to transport 10^{21} kg of HSE-bearing core melt upwards into the mantle. Such piecemeal delivery will clearly increase the transport time and is linked intimately to the bombardment flux. A problem here is that surface impactors will themselves add new mass to the planet.

Discussion: Despite some problems, we argue that our model of return flow means that at least some of the ‘late veneer’ component in the present day Earth could be internal in origin [e.g. 13], but triggered by external impacts. If a portion of the siderophile element mantle abundance is provided by core-mantle interaction, then this may help explain lunar data being used to explore the possible nature of a late veneer material. Whereas lunar impact melt rocks (crust) show some high abundances of HSE and may contain evidence of a late accretion event [3], the lunar mantle contains low concentrations of HSE and lunar highlands breccias apparently have a significant positive Ru anomaly, similar to rocks in the Earth's mantle, and unlike any chondrite [14]. Currently, there are no known ways to fractionate PGEs to yield this type of pattern in nebular processes and at this point no reason to suggest an unknown chondrite type that provides all that siderophile element flux. While core-derived siderophile input, followed by mixing and dispersal in the overlying mantle remains speculative, it has potential for answering questions and stimulating research on the HSE mantle paradox.