Program
Differentiation: Building the Internal Architecture of Planets

May 7–10, 2018 • Pasadena, California

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Universities Space Research Association

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## Guide to Sessions

### Tuesday, May 8, 2018

- **8:30 a.m.** International East  The Big Picture
- **10:25 a.m.** International East  Partially Differentiated Asteroids
- **1:30 p.m.** International East  Icy Bodies
- **2:55 p.m.** International East  Vesta

### Wednesday, May 9, 2018

- **8:30 a.m.** International East  Differentiated Meteorite Parent Bodies
- **9:30 a.m.** International East  Lunar Magma Ocean
- **1:30 p.m.** International East  Lunar Evolution and Dynamo
- **3:10 p.m.** International East  Mars

### Thursday, May 10, 2018

- **8:30 a.m.** International East  Earth: Crust, Mantle, and Dynamo
- **1:30 p.m.** International East  Earth: Core Formation
Program

Tuesday, May 8, 2018
THE BIG PICTURE
8:30 a.m.  International East

Chair: Walter Kiefer

8:30 a.m.  Kiefer W. S.  [*]
Welcome and Overview

8:35 a.m.  Desch S. J.  [*]  [INVITED]
New Developments in Accretion and Differentiation [#4038]
I review some new developments in our thinking of how terrestrial planets and Kuiper belt objects grow and differentiate.

9:00 a.m.  Kruijer T. S.  Burkhardt C.  Budde G.  Kleine T.  [*]  [INVITED]
Meteorite Dichotomy Implies that Jupiter Formed Early [#4037]
Meteorites derive from two distinct nebular reservoirs that co-existed and remained spatially separated between ~1 and ~3–4 Ma after CAIs. This can most easily be explained if Jupiter acted as a barrier and formed early, within less than ~1 Ma.

9:25 a.m.  Dunlap D. R.  Wadhwa M.
Chronology of Planetesimal Differentiation Based on the Timing of Achondrite Formation in the Early Solar System [#4003]
Chronology of achondrites provide critical insights into accretion and differentiation timescales in the early solar system. A diverse suite of achondrites are presented here to constrain the thermal histories of a number of distinct planetesimals.

9:45 a.m.  Shahar A.  Elardo S. M.  Young E. D.  Schlichting H. E.  Caracas R.  Sio C. K. I.  Bennett N. R.  [*]  [INVITED]
Using Stable Isotopes to Probe Planetary Differentiation and Evolution [#4021]
This talk will focus on how stable isotope ratios can inform us about the differentiation and evolution of planetesimals.

10:10 a.m.  Break
Chair: Nancy Chabot

10:25 a.m. Goodrich C. A. *
Siderophile Element Fractionation in Metal in Ureilites: Challenging the Definition of Primitive Achondrites [#4028]
Ureilites do not conform to the definition of primitive achondrites. I address aspects of this problem involving oxygen isotopes and siderophile elements in metal.

10:45 a.m. Dhaliwal J. K. *  Chabot N. L.  Ash R. D.  McCoy T. J.  [INVITED]
An Experimental Analog for Metal-Sulfide Partitioning in Acapulcoite-Lodranite Meteorites [#4020]
This study builds on prior analyses of highly siderophile element (HSE) abundances in primitive achondrites. We performed melting experiments of naturally occurring FeNi and FeS to examine the effect of sulfur on HSE inter-element partitioning.

11:10 a.m. Crossley S. D. *  Ash R. D.  Sunshine J. M.  McCoy T. J.  Corrigan C. M.
Oxidized Primitive Achondrites Sample Distinct Parent Bodies [#4040]
We present our current findings regarding the formation of a collection of brachinites and similar ungrouped achondrites under different redox conditions and extents of core segregation.

11:30 a.m. GENERAL DISCUSSION

12:00 p.m. Lunch
Tuesday, May 8, 2018
ICY BODIES
1:30 p.m. International East

Chair: Walter Kiefer

1:30 p.m. Travis B. J. * Bland P. A. [INVITED]
A Mudball Model for the Evolution of Carbonaceous Asteroids [#4024]
We simulate the evolution of carbonaceous chondrite parent bodies from initially unconsolidated aggregations of rock grains and ice crystals. Application of the numerical model MAGHNUM to evolution of CM type planetesimals and Ceres is described.

1:55 p.m. Castillo-Rogez J. C. * Neveu M. N. Ermakov A. I. King S. D. Raymond C. A.
Chemical Differentiation in Large Icy Bodies — Application to Ceres and Europa [#4029]
This work reviews the impact of aqueous alteration on the physical evolution of large ice-rich bodies.

2:15 p.m. Raymond C. A. * Castillo-Rogez J. C. McSween H. Y. Russell C. T. [INVITED]
Divergent Evolutionary Paths of Vesta and Ceres [#4044]
Dawn revealed Vesta to have a complex magmatic evolution starting from a volatile-poor original composition. By contrast, Ceres formed with a significant fraction of volatiles which drove it down a very different evolutionary path.

2:40 p.m. Break
Early and Rapid Differentiation of Vesta

Al-Mg dating on eucrites and diogenites reveals that the differentiation and the establishment of a crust on Vesta occurred within the 3 Ma of the solar system.

Constraining the Timing of the Vestan Dynamo

Crystallization age of unique magnetized diogenite NWA 5480 is obtained to constrain the timing of core dynamo and mantle convection in asteroid 4 Vesta.

Thermal Implications of the Iron Rain Model for Core Formation on Asteroid 4 Vesta

The abundance of moderately siderophile elements on Vesta implies that core formation occurred by iron rain sinking through a silicate magma ocean. This requires an internal temperature of at least 1400–1475°C and very rapid accretion.

Trace Element Abundances in Eucrite Basalts: Enrichment or Depletion?

It is not clear how incompatible trace element (ITE) variation in eucrite basalts originated. Here, mechanisms for relative ITE enrichment or depletion are experimentally evaluated in an attempt to reconcile the Stannern and main group eucrites.
DIFFERENTIATED METEORITE PARENT BODIES
8:30 a.m. International East

Chair: Cyrena Goodrich

8:30 a.m. Chabot N. L. *
Ungrouped Irons and Early Solar System Metallic Cores [#4001]
Iron meteorites provide unique opportunities to investigate differentiation processes in the early solar system. But how many metallic cores are represented in our meteorite collections?

8:50 a.m. Hoffmann V. H. * Mikouchi T. Hochleitner R. Kaliwoda M. Wimmer K.
Unique NWA 11119/11558, NWA 7325 (and Pairs) and Almahata Sitta Individuals MS-MU 011/035: New Light on Very Early Parent Body Differentiation [#4018]
The preliminary results would support our conclusion that these unique meteorites may probe the crust/upper mantle of a yet unknown planetary body which existed only in a very early period of time of our planetary system.

9:10 a.m. Lyons R. J. * Bowling T. J. Ciesla F. J. Davison T. M. Collins G. S.
Effect of Impacts on the Cooling Rates of Differentiated Planetesimals [#4036]
I have modeled planetesimal impacts in the early solar system, following their formation, differentiation, and cooling. I found that small collisions can expose the core, resulting in more than an order of magnitude increase in the cooling rates.
Chair: Kevin Righter

9:30 a.m.  Draper D. S. *  Prissel T. C.
*A Review of Experimental Studies Simulating Lunar Magma Ocean Solidification [#4006]*
We review petrologic experiments conducted over the past decade aimed at simulating crystallization of a range of lunar magma ocean compositions under a variety of conditions.

9:50 a.m.  Break

10:05 a.m.  Kring D. A. *  Needham D. H.
*Using the South Pole-Aitken (SPA) Impact Melt Composition to Infer Upper Mantle Mineralogy and Timing of Potential Mantle Overturn [#4011]*
Observed melt composition within the SPA basin are consistent with an impact prior to mantle overturn, when the upper mantle contained clinopyroxene rather than olivine. Potentially, the impact triggered mantle overturn.

10:25 a.m.  Elardo S. M. *  Laneuville M.  McCubbin F. M.  Shearer C. K.
*Asymmetric Post-Magma Ocean Crust-Building on the Lunar Nearside [#4022]*
Our experiments show that the KREEP reservoir on the lunar nearside reduces the melting temperature of Mg-suite source rocks, leading to asymmetric crust-building magmatism independent of any contribution from radiogenic heating.

10:45 a.m.  Treiman A. H. *  Gross J.
*The Lunar Magma Ocean (LMO) Paradigm Versus the Realities of Lunar Anorthosites [#4033]*
The paradigm of the Lunar Magma Ocean (LMO) is inconsistent with much chemical and compositional data on lunar anorthosites. The paradigm of serial anorthosite diapirism is more consistent, though not a panacea.

11:05 a.m.  Treiman A. H. *
*Late Planetary Differentiation: Lunar ‘KREEP’ as a Local Product [#4030]*
KREEP is not everywhere, and all KREEP is not the same. Think globally, KREEP locally.

11:20 a.m.  GENERAL DISCUSSION

12:00 p.m.  Lunch
Chair: Stephen Elardo

1:30 p.m. Boukare C.-E. * Parmentier E. M. Parman S. W. **CANCELED**
Cumulate Mantle Dynamics Response to Magma Ocean Cooling Rate [#4046]
We investigate the issue of the cumulate compaction during magma ocean solidification. We show that the cooling rate of the magma ocean affects the amount and distribution of retained melt in the cumulate layers and the timing of cumulate overturn.

1:50 p.m. Caracas R. * Stewart S. T.
Silicate Melts of the Protolunar Disk and the Formation of the Magma Ocean from AB Initio Simulations [#4004]
We employ large-scale first-principles molecular dynamics simulations to understand the physical and chemical behavior of the evolution of the molten protolunar disk from its formation all the way to the crystallization of the magma ocean.

2:10 p.m. Piet H. * Badro J. Gillet P.
Geochemical Constraints on the Size of the Moon — Forming Giant Impact [#4008]
We use the partitioning of siderophile trace elements to model the geochemical influence of the Moon-forming giant impact on Earth’s mantle during core formation. We find the size of the impactor to be 15% of Earth mass or smaller.

2:30 p.m. Tikoo S. M. * [INVITED]
Paleomagnetic Records of Ancient Core Dynamos [#4042]
We review paleomagnetic results that constrain the field intensities and longevities of ancient core dynamos operating within the Moon as well as within the parent bodies of several meteorite classes.

2:55 p.m. Break
Wednesday, May 9, 2018
MARS
3:10 p.m.  International East

Chair: Vinciane Debaille

3:10 p.m.  O’Rourke J. G. * Shim S.-H.
Suppressing the Martian Dynamo with Hydrogenation of the Core by Hydrated Mantle Minerals [#4012]
A magnetic murder mystery on Mars! What killed the dynamo around 4 Ga? Maybe hydrogenation of the core, but models are sensitive to the compositional structure of the mantle after differentiation.

3:30 p.m.  Jones J. H. * Simon J. I.
The Differentiation of Mars and Its Shergottite Source Regions [#4025]
Whole-rock Sm-Nd "isochrons" of shergottites are best interpreted as mixing lines, not as ages.

3:50 p.m.  Armatage R. M. G. * Debaille V. Brandon A. D. Agee C. B.
Meteoritic Evidence for Multiple Early Enriched Reservoirs in the Martian Mantle [#4005]
From isotopic systematics, the martian crustal reservoir represented by NWA 7034 cannot be the enriched end-member for the shergottites. This suggests multiple enriched reservoirs in the martian mantle formed by several differentiation events.

4:10 p.m.  Phillips M. S. * Moersch J. E. Viviano C. E.
Feldspathic Rock in Ancient Crust, N. Hellas, Mars: Implications for Early Mantle Conditions [#4026]
Reflectance spectroscopy of northern Hellas massifs reveals and abundance of feldspathic rocks.

4:30 p.m. GENERAL DISCUSSION
Thursday, May 10, 2018
EARTH: CRUST, MANTLE, AND DYNAMO
8:30 a.m. International East

Chairs: Rosalind Armytage
David Draper

8:30 a.m. Sikdar J. *   Rai V. K.   CANCELED
Si Isotopes in Enstatite Chondrites: Implications to Accretion and Differentiation Event of the Earth [#4032]
The abstract summarizes the recent results on high precision Si isotope analyses in various micro milled components of Enstatite chondrites with implications towards the accretion and primary differentiation event of the Earth.

8:50 a.m. Baker D. R. *
Planetary Differentiation by Aerial Metasomatism [#4009]
Dissolution of surficial rocks will occur on planetary bodies with steam atmospheres. Although the amount of dissolved material is small, metasomatism of chondritic compositions produces siliceous crustal materials and enriches residual rocks.

9:10 a.m. Putirka K. D. *   Rarick J.
The Composition and Mineralogy of Exoplanets, Using the Hypatia Catalogue: Implications for Extrasolar Plate Tectonics and Mantle Convection [#4010]
Many exoplanets have pyroxenite mantle mineralogies, which may impede plate tectonics, due higher mantle viscosities and lid yield strengths; majorite-rich transition zones on these may also prevent subducted slabs from reaching lower mantle depths.

9:30 a.m. Heinze W. D. *
The Roll of the Dice: Differentiation Outcomes and the Role of Late Protoplanetary Impacts [#4027]
Because late accretion occurs by the impact of 10–100 (large) embryos which have low probability of being high-velocity events and such events are necessary for magnetic dynamos, small number statics control differentiation outcomes.

9:50 a.m. Break

10:05 a.m. Moore W. B. *   Simon J. I.
Heat Pipe Planets [#4039]
We propose that cooling via volcanic heat pipes may provide a universal model of the way terrestrial bodies transition from a magma-ocean state into subsequent single-plate, stagnant-lid convection or plate tectonic phases.

10:25 a.m. Stegman D. R. *   Badro J.
Source Regions for the Earth's Magnetic Field During the First Billion Years [#4041]
Earth's early magnetic field places a severe constraint on the thermal evolution of the mantle and core. We will present how a dynamo in a basal magma ocean can reconcile major outstanding issues with present models.

10:45 a.m. Wainwright A. N. *   Debaille V.   Zincone S. A.
Archean Isotope Anomalies as a Window into the Differentiation History of the Earth [#4015]
No resolvable $^{142}$Nd anomaly was detected in Paleo- Mesoarchean rocks of São Francisco and West African cratons. The lack of $^{142}$Nd anomalies outside of North America and Greenland implies the Earth differentiated into at least two distinct domains.
11:05 a.m. Schaefer L. * Elkins-Tanton L. T. Pahlevan K.
Ferric Iron Production in Magma Oceans and Evolution of Mantle Oxidation State [4019]
Self-oxidation of the magma ocean by ferric iron production at high pressure may explain the mantle oxidation state of the Earth. Partitioning during fractional crystallization can further increase the mantle oxygen fugacity during solidification.

11:25 a.m. GENERAL DISCUSSION

12:00 p.m. Lunch
Thursday, May 10, 2018
EARTH: CORE FORMATION
1:30 p.m. International East

Chairs: Kevin Righter
Nancy Chabot

1:30 p.m. Fischer R. A. * Nimmo F. O'Brien D. P. [INVITED]
What can the Hf-W System tell Us About the Mechanism and Timing of Earth's Core Formation? [#4007]
Strong tradeoff between effects of depth and extent of metal-silicate equilibration and formation timescale on the Hf-W system. Whole mantle equilibration requires k ≈ 0.4. Later formation times require less equilibration to match Earth's anomaly.

1:55 p.m. Jackson C. R. M. * Bennett N. R. Du Z. Cottrell E. Fei Y. [INVITED]
Early Episodes of High-Pressure Core Formation Preserved in Plume Mantle [#4016]
New experiments demonstrate that xenon isotopes are sensitive to core formation. This behavior may be crucial in explaining the co-occurrence xenon and tungsten anomalies recently observed in plume mantle.

2:20 p.m. Jackson C. R. M. * Du Z. Bennett N. R. Fei Y. Cottrell E.
Sequestration of Nitrogen in the Core During Accretion [#4017]
Nitrogen is depleted in bulk silicate Earth relative to other volatiles. New partitioning experiments suggest high pressure core formation may be responsible for this depletion.

2:35 p.m. Break

2:50 p.m. Badro J. *
Metal-Silicate Partitioning Experiments at Core-Mantle Boundary Conditions: Core-Mantle Interactions — Past and Present [#4031]
I will discuss some recent results focusing the partitioning mantle components (SiO₂, FeO, MgO) in core-forming metal at extreme conditions relevant to Earth's core-mantle boundary.

3:10 p.m. Righter K. * Schonbachler M.
Ag Isotopic Evolution of the Mantle During Accretion: New Constraints from Pd and Ag Metal-Silicate Partitioning [#4034]
Using new metal-silicate partitioning constraints we calculate Ag isotopic composition of the terrestrial and martian mantle.

3:30 p.m. Klaver M. * Elliott T.
Non-Chondritic Ni Isotope Composition of the Bulk Silicate Earth [#4035]
We present high-precision Ni isotope data of chondritic meteorites and carefully selected mantle peridotites. These data show that the Bulk Silicate Earth is ca. 90 ppm lighter than chondritic meteorites, possibly as the result of core formation.

3:50 p.m. Elardo S. M. * Shahar A. Caracas R. Mock T. D. Sio C. K. I.
The Effects of Core Composition on Iron Isotope Fractionation During Planetary Differentiation [#4023]
High pressure and temperature isotope exchange experiments and density functional theory calculations show how the composition of planetary cores affects the fractionation of iron isotopes during planetary differentiation.

4:05 p.m. GENERAL DISCUSSION

4:50 p.m. Kiefer W. S. *
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METEORITIC EVIDENCE FOR MULTIPLE EARLY ENRICHED RESERVOIRS IN THE MARTIAN MANTLE R.M.G. Armytage1,2, V. Debaillé1, A.D. Brandon1, C.B. Agee3 1Laboratoire G-Time, CP 160/02, Université Libre de Bruxelles, Ave F. Roosevelt 50, 1050 Bruxelles, Belgium. 2Jacobs/JETS, NASA Johnson Space Center, 2102 NASA Parkway, Mailcode X13, Houston, TX, 77058, (email: rosalind.m.armytage@ nasa.gov), 3Earth and Atmospheric Sciences, University of Houston, Houston, TX, 77204, USA 4Institute of Meteoritics, University of New Mexico, Albuquerque, NM, USA

Introduction: Shergottite meteorites are the largest group of martian meteorites currently represented in our collection. Resolving the possible mantle and crustal sources for shergottites is crucial for understanding the formation and early differentiation of Mars. On the basis of their bulk incompatible trace element compositions and Sm-Nd systematics, shergottites form a compositional continuum that can be subdivided into enriched, intermediate, and depleted subgroups [e.g. 1]. However, the textural diversity and major element variations exhibited by the shergottites do not correlate with these subgroups, making it difficult to explain the compositional continuum in terms of simple crustal assimilation and fractional crystallization [e.g. 2-4]. In addition, orbiter and rover characterization of the martian surface reveal that the major element composition of most of its surface does not match the shergottites [5] leaving the relationship between them poorly understood. The identification of the meteorite NWA 7034 and its pairs as a Mars surface rock [6-8] provides access to a representative sample of Mars’ crust.

To investigate the relationship between crustal reservoir sampled by NWA 7034 and the enriched end-member for shergottites, we utilized the short-lived 146Sm-142Nd, and long-lived 147Sm,143Nd and 176Lu-176Hf chronometers, which are sensitive to silicate differentiation. We analysed three fragments of NWA 7034 for each isotope system in order to evaluate the degree of heterogeneity in the meteorite, given that it is a polymict breccia [8,9].

Method: The three fragments (~0.1g) were digested in HF-HNO3 in Parr Bombs, and aliquots to measure trace elements and spiked Sm, Nd, Lu, and Hf were removed. The Hf and Nd for isotopic analysis were separated using ion-exchange chromatography. A TritonPlus was used to collect the Nd isotopic data, while the Hf isotopic ratios and the spiked aliquots were measured on a NuPlasma HR, both at ULB. The trace element data was collected using an Agilent ICP-MS also at ULB.

Results and Discussion: The rare earth element (REE) compositions for the three fragments were consistent with the “bulk” breccia composition identified in [8], displaying a profile that resembles a 4% melt of a primitive mantle composition. The very negative mean isotopic compositions for this breccia, $\mu^{142}\text{Nd}_{\text{Nd}} = -45 \pm 5$ (2SD), $\epsilon^{143}\text{Nd}_{\text{CHUR}} = -16.7 \pm 0.4$ (2SD) and $\epsilon^{176}\text{Hf}_{\text{CHUR}} = -61 \pm 9$ (2SD) point to an ancient origin for this martian crust.

As in [7], the $\epsilon^{143}\text{Nd}$ versus La/Yb for NWA 7034 plots as an enriched end-member on a two-component mixing hyperbola for shergottites with the least-squares regression (LSR) curve being reproduced by mixing between NWA 7034 and the depleted shergottite QUE 94201. However, this apparent corroboration of crustal contamination of the shergottites is not strongly supported by our new $\epsilon^{176}\text{Hf}$ data as the LSR curve cannot be satisfactorily reconstructed with any other depleted martian meteorite as the depleted end-member if NWA 7034 is taken as the enriched reservoir. Further modelling of the source reservoirs for the shergottites shows that the crust sampled by NWA 7034 possesses a Hf/Nd ratio that is incompatible with this crustal reservoir being an end-member that generated the shergottite source mixing array. This is also borne out by the $\mu^{142}\text{Nd}-\epsilon^{143}\text{Nd}$ model ages for NWA 7034.

Despite a REE profile that matches a primitive mantle melt, the isotopic data from this study requires that the NWA 7034 crustal reservoir is not juvenile but has experienced a multi-stage formation history, and does not possess a clear isotopic or trace element link with the reservoirs that produced the shergottites. Instead mantle reservoirs formed via other early differentiation processes such as in a Mars magma ocean must be responsible for the trace element and isotopic compositions of the shergottites sources.

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(\text{SiO}_2, \text{FeO}, \text{MgO}) IN CORE-FORMING METAL AT THOSE EXTREME CONDITIONS. WHILE THESE LITHOPHILE COMPONENTS ARE NOT EXPECTED TO HAVE ANY AFFINITY FOR THE METAL, THEY READILY DISSOLVE AT THE HIGH TEMPERATURE CONDITIONS [5–6] OF THE CORE-MANTLE BOUNDARY. BEING ABLE TO REPRODUCE SUCH EXTREME CONDITIONS HAS PROVED CRUCIAL TO FIRST ELUCIDATE THOSE EFFECTS AND THEN QUANTIFY THEM; IN THIS SENSE, USING THE LHDAC TO STUDY CORE-MANTLE INTERACTION ISN’T A MERE QUANTITATIVE ADVANCE OVER PREVIOUS GENERATIONS OF EXPERIMENTS, BUT A QUALITATIVE JUMP RADICALLY CHANGING OUR UNDERSTANDING OF THE PROCESSES OCCURRING IN THOSE CONDITIONS.

I WILL SHOW THAT THE PARTITIONING OF EARTH’S THREE MOST ABUNDANT LITHOPHILE ELEMENTS (Mg, Si, AND O) INTO THE CORE DEPENDS ON TEMPERATURE AND COMPOSITION, BUT NOT ON PRESSURE. HENCE, THE RESULTS DESCRIBED HERE ARE ALSO VALID FOR OTHER TERRESTRIAL (EXO-)PLANETS.

I WILL ALSO DISCUSS THE GENERATION OF AN EXSOULUTION-DRIVEN DYNAMO [7–9], AND SHOW THAT MgO EXSOULUTION FROM THE CORE DURING SECULAR COOLING, CONSTRAINED BY OVER 50 NEW OR RECENT EXPERIMENTS, CAN PRODUCE A DIPOLAR MAGNETIC FIELD IN THE RANGE 40–80 nT (I.E. ON THE ORDER OR SLIGHTLY STRONGER THAN THE PRESEND-DAY FIELD) ON EARTH’S SURFACE PRIOR TO INNER-CORE GROWTH, PROVIDING AN EXPLANATION FOR PALEOMAGNETIC OBSERVATIONS OF SUCH FIELDS GOING ALL THE WAY BACK INTO THE EARLY EARTH [10–12].

REFERENCES:

PLANETARY DIFFERENTIATION BY AERIAL METASOMATISM. D. R. Baker, Earth and Planetary Sciences, McGill University, 3450 rue University, Montreal, QC, Canada H3A 0E8, don.baker@mcgill.ca.

**Introduction:** The existence of steam-dominated planetary atmospheres early in the lifetime of Earth and similar-composition planets has long been recognized [1]. However, the role of steam atmospheres in the formation of early, silica-rich, crystalline crustal material from chondritic sources and the resulting planetary differentiation has only recently been investigated [2, 3, 4]. These studies agree that during degassing of magma oceans, or interaction between steam-dominated atmospheres and rocky lids over magma oceans, the incongruent dissolution of ultramafic rocks into fluids occurs, producing solute compositions similar to Earth's modern crust that could result in silicate rains onto the planetary surface [3]. This is the process entitled aerial metasomatism.

**Mass of siliceous material:** Experimental studies over a range of pressures and temperatures from that at the surface of an Earth-sized planet enveloped within a steam atmosphere to mantle depths on the order of 50 km indicate that hydrous fluids in equilibrium with peridotite contain between 1 to 10 % silicic solute [3]. The total amount of solute depends upon the initial water concentration in the planetary body and the extent of degassing. Single-stage degassing of a near-chondritic planetary bulk composition with water concentrations similar to CI carbonaceous chondrites, 10-20 wt. %, produces ~ 1-2 wt. % (of the initial rock) siliceous material. Starting with low water concentrations, similar to the Bulk Silicate Earth, 2700 ppm [5], would only yield ~0.03 wt. % siliceous solute. Nevertheless, for Earth the latter fraction produces 10^{21} kg of siliceous, crust-like material from the mantle, equivalent to 5 % of Earth's modern crustal mass [3]. Multistage dissolution-precipitation cycles (dissolution at the surface and precipitation of silicate rain at altitude in the atmosphere) during the 0.1 (Mars) to 1 (Earth) to 10 (Venus) million year lifetime of steam atmospheres on terrestrial planets [6] can be envisioned that would enhance the mass of crustal material produced by this mechanism of aerial metasomatism, but quantifying the mass of solute produced by these processes is unconstrained. Nor can we constrain the intensity of the silicate rain deluge that occurred when the atmosphere cooled to the temperature at which oceans condensed.

These estimates of the mass of material produced metasomatically are not inconsistent with isotopically constrained models of continental growth requiring the formation of ~ 20 % of the siliceous continental mass within the 1e billion years of Earth history (e.g., [7]). Production of such large amounts of crust by mantle melting at this time are unlikely because of high potential mantle temperatures resulting in the genesis of ultramafic magmas [8], not siliceous ones.

**Effect on trace element composition of the residual mantle:** Trace element partitioning measured in one experiment of [3] by LA-ICP-MS demonstrates that trace elements (REE, Zr, Hf, Rh, Ba, Th, U, Pb) are sparingly soluble in the fluid (i.e., more compatible in the crystalline solid) and little inter-element fractionation occurs, similar to previous results obtained at higher pressures by other researchers. The residua after metasomatism is enriched proportionally to the amount of lost fluid. Thus, the residua of a chondritic body undergoing 10 % fluid loss would be enriched ~10 % by the metasomatic process.

**Conclusions:** Aerial metasomatism will occur on planetary bodies with steam atmospheres. Although the amount of dissolved material is small, metasomatism of chondritic compositions produces siliceous crustal materials as solutes and slightly enriches the original rocks in trace elements. This process has the potential to play an important role in planetary differentiation.

Summary: Magma ocean (MO) fractional crystallization has been proposed to generate gravitationally unstable Fe-Mg chemical stratification capable of driving solid-state mantle overturn [1]. Fractional solidification and overturn hypothesis, while only an ideal limiting case, can explain important geochemical features of both the Moon and Mars. Recent models of MO cumulate dynamics have shown that cumulate overturn can occur during MO solidification if the cumulate viscosity is low enough or the time of solidification is long enough [e.g., 2, 3]. Nevertheless, these models do not consider (1) the effect of retained melt on cumulate viscosity and (2) substantial variation in the rate of solidification during MO solidification. Here, we investigate the issue of the cumulate compaction during MO solidification. We show that the cooling rate of the magma ocean affects the amount and distribution of retained melt in the cumulate layers. The retained melt controls the viscosity of the cumulates and the effective chemical partitioning between the residual magma ocean and the cumulate.

Model: We consider an ideal case where a liquid layer lies above a viscous cumulates that contains interstitial melt. As solidification proceeds, layers of small but finite thickness are deposited at the top of the cumulate pile at a rheological critical melt fraction (RCMF) of ~35-40%. of melt. As the melt is buoyant in the cumulate, it tends to rise upwards towards the residual magma ocean by percolation limited by cumulate compaction. We solve the compaction problem in 1D in the cumulate layers in a similar approach as the one proposed by [4]. The main parameters that govern the dynamics are: the compaction length δ, the segregation flux of reference S_{ref} and the crystal sedimentation velocity, v_{sed}. If v_{sed} exceeds a critical value [6], (v_{sed} ~ S_{ref}), the cumulates layers cannot compact during crystal deposition. If v_{sed} remains below this critical value, the cumulate layers compact. In this case, lower v_{sed} results in lower retained melt fraction. Here, v_{sed} is assumed to reflect perfectly the time of MO solidification: v_{sed} = H/τ_{MO}. We investigate three timescales of MO solidification that approximate MO cooling by pure black-body radiation (τ_{MO} = 10^{-2} Myr), thermal radiation inhibited by an opaque atmosphere (τ_{MO} = 1 Myr) or MO cooling through a conductive lid (τ_{MO} = 100 Myr). For the Moon, these preliminary results suggest that the cumulate should not overturn during the early stages of MO solidification when solidification is fast (τ_{MO} < 10^{-3} Myr). Even though the cumulate viscosity is relatively low (about 10^{16} Pa s). Assuming that a decrease in the MO cooling rate implies a decrease of v_{sed} the cumulate would compact and expel melt as the MO cooling rate drops due to the formation of the plagioclase-rich conductive lid.

Siilicate melts of the protolunar disk and the formation of the magma ocean from ab initio simulations.

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We employ large-scale first-principles molecular dynamics simulations to understand the physical and chemical behavior of the evolution of the molten protolunar disk, at the atomic level, from its formation all the way to the crystallization of the magma ocean.

We consider pyrolite as the average composition of the Earth’s mantle. We cover the 0.75 – 7.5 g/cm³ density range and 2000 – 10000 K temperature range. This allows us to investigate the entire disk, from the interior of the molten core to the outer regions of the vaporized disk.

At low density and low temperatures, in the 2000 to 4000 K range, we capture the nucleation of bubbles. The bubbles contain a low-density gas phase rich in individual alkaline and calc-alkaline cations and SiO₂ groups. When volatiles are present in the system, such as CO and CO₂, these molecular species are the first ones to evaporate and be present in these bubbles. The degassing is present in all the outer parts of the disk.

Then we interpret the bubble nucleation in terms of the liquid-vapor equilibrium and the supercritical point. This allows us to separate the liquids droplets that will condense to form the magma ocean.
Introduction: Large volatile-rich bodies were subject to ice melting either during their early history or due to short-lived radioisotope decay and/or accretional heating. These bodies are expected to undergo aqueous alteration whose extent depends on the temperature reached in the ocean and other environmental parameters such as pH and redox conditions. Evidence for salts has been found at most large icy bodies, which reflects the leaching of certain elements from the rock, such as alkali and alkaline earth metals during that period of hydrothermal alteration. Important implications of leaching include the displacement a fraction of the potassium from the rock phase to the hydrosphere [1, 2] and the sequestration of the iron and other metals in oxides and sulfides [e.g., 3]. Chemical alteration also impacts thermophysical properties and introduces new materials (salts, hydrates) in the shells of icy bodies [4]. Interior models have not integrated these important processes in a self-consistent manner. We quantify chemical differentiation and its impact on the physical evolution of Ceres and Europa.

Approach: This work combines geochemical modeling with the Geochemist’s Workbench software and FREZCHEM software [4] and thermal evolution modeling previously applied to Titan and Ceres [e.g., 5]. A major process that has not been properly approached to this point is the quantification of the extent of aqueous alteration in any object. Observations of Ceres by the Dawn mission indicate that alteration was rather advanced as illustrated by the abundance of Mg-serpentine and carbonates [6]. However, it is not possible to definitely conclude, within the uncertainties of Dawn’s infrared measurements, that the conditions in Ceres’ early history led to chemical equilibrium. Additional processes can contribute to further differentiation but are not well modeled, such as the preferential accumulation of metal-rich particles in a core [3].

Applications: We focus on Ceres and Europa as chemical alteration can significantly alter their thermal evolution and current states with astrobiological implications. Data returned by the Dawn mission provide a reference framework for this study. We use that information to assess the impact of chemical fractionation on the long-term evolution of Europa’s rocky mantle.

Application to Ceres. The Dawn mission has returned important constraints on the interior of Ceres, showing that it is differentiated in a rock dominated mantle and a volatile-rich shell with a density ~1.3 g/cm³ [7]. However, the latter is stronger than ice by more than three orders of magnitude, which suggests a large fraction of hydrates [7, 8]. The formation of gas hydrates upon freezing is expected for pressures of a few MPa [4]. Hence it is likely Ceres’ icy crust is a mixture of ice, clathrate hydrates, salts (especially hydrated), organics, and a small fraction of phyllosilicates, as well as macroporosity. Most organics have a low density and could be stored in the crust during Ceres’ early differentiation phase. Our thermal modeling accounts for the depressed thermal conductivity of hydrates with respect to ice and (to a lower extent), the impact of porosity. The detection of ammonium in the clays [9] indicates advanced removal of potassium from the silicates [1,2]. Modeling with FREZCHEM suggests that potassium is not incorporated in the icy shell upon freezing and instead concentrates in the form of chlorides in the residual liquid [4], presumably the pore fluid inferred from topography relaxation [8]. Dawn’s geophysical data is consistent with (but does not require) the presence of a small iron core that may result from the accumulation of sulfide- and magnetite-rich particles [10]. While these processes occurred during Ceres’ first 100 My, the resulting thermal conductivity structure and redistribution of potassium can explain the long-term preservation of temperatures above the eutectic temperatures of chlorides, consistent with Dawn’s observations [8].

Application to Europa. A major difference between Europa and Ceres may be that the former did not accrete ammonia. However, Europa is expected to have undergone advanced aqueous alteration as well [11]. Accounting for the feedbacks between physics and chemistry is expected to produce cooler conditions in the rocky mantle, thus preventing silicate dehydration and the differentiation of a metallic core.


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**Introduction:** There are two types of basaltic eucrites, the main and Stannern groups, which have similar major element compositions but widely different abundances of incompatible trace elements (ITEs). It is not clear if this difference reflects addition of, or removal of, ITEs. The HED meteorites (howardites, eucrites, diogenites) are inferred to be samples of the crust of 4 Vesta, or similar, formed in a magma ocean episode, and present a unique opportunity to understand planetary differentiation in the early solar system [1-4]. The eucrites are basalts and gabbros, composed of sub-equal proportions of low-Ca pyroxene (pigeonite) and anorthitic plagioclase [5]. Main group eucrites have ITE abundances at ~10x CI, and are likely to have crystallized directly from a magma ocean [6] as its crust [1]. More detailed modeling suggests that eucrite compositions represent those of extracted liquids formed by extensive equilibrium crystallization of the magma ocean [7]. Stannern group eucrites have higher abundances of ITE, ~ 20x CI, and are difficult to explain within a magma ocean model. If the Stannern and main group eucrites are related, then there must be a mechanism that decouples ITEs from major elements. A number of mechanisms have been suggested, and the most successful is that ITEs become concentrated in low-degree partial melts of the crust [8], which are then assimilated into main group eucrite magma bodies. Here, experimental results are used to address the plausibility of this model, and propose an alternative.

**Methods:** I report experimental results in press [9], in which samples of an unequilibrated eucrite, Northwest Africa (NWA) 7035, were heated to above its solidus (under reducing conditions). A unequilibrated eucrite was chosen as representative of unmetamorphosed eucritic crust, contrary to earlier models that used a metamorphosed eucrite [8,10], hypothetically of a deep crustal origin. Using an unequilibrated eucrite allows that impact processes may have supplied the heat source for metamorphism, rather than relying on direct heating from the magma ocean. Resultant compositions of the low-volume partial melts and the restite minerals were analyzed by EMPA and LA-ICP-MS at the University of Alberta.

**Discussion:** Experimentally produced partial melts are strongly enriched in ITEs (up to ~50x CI for a reasonably extractable melt), but their abundances were not completely decoupled from those of major elements (e.g. Mg#, or non-ITEs (e.g. Sc). In the magma mixing model [8], a minimum of ~20% of the partial melt material is required to generate the 20x CI ITE enrichment from extractable melts. Assimilating such melts would cause a substantial shift in Mg# and Sc. Similar incomplete decoupling was observed in the partial melting of an equilibrated eucrite [10].

It may be possible to modify the model to generate melts more consistent with the Stannern trend. For example, experimental results showed that the Sc contents of partial melts decreased as experiment duration increased, so it is conceivable that a long-duration equilibration would lower the Sc content to match the main group. However, to produce melts with a suitably high Mg# would require a more magnesian starting material. Specifically, the portion of pyroxene that melts would have to have the same average Mg# as the main group, which restricts the model to more magnesian starting materials, i.e. cumulate eucrites. The partial melts’ enhanced ITE abundances arose because they incorporated large proportions of mesostasis material. If metamorphic temperatures had been above the solidus, ITE-rich mesostasis could have been extracted and leave ITE-depleted restites. Metamorphism could then erase the major element evidence of melt extraction (mineral chemical zoning), making it appear that ITEs had been decoupled. This model is effectively an inversion of the common model [8]; Stannern group eucrites would be direct products of magma ocean crystallization, and main-group eucrites would be restites (or formed from restites) after extraction of low-volume partial melts.

UNGROUPED IRONS AND EARLY SOLAR SYSTEM METALLIC CORES. Nancy L. Chabot, Johns Hopkins Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723, USA (Nancy.Chabot@jhuapl.edu).

Introduction: Iron meteorites that sample the central metallic cores of asteroid-sized bodies provide unique opportunities to investigate differentiation processes in the early Solar System. But how many metallic cores are represented in our meteorite collections? There is general agreement that there are 11 “magmatic” groups [e.g. 1], which provide samples of likely 10 different asteroidal cores [2], and a few groups of “non-magmatic” irons that do not sample central metallic cores [e.g. 3]. However, iron meteorites are often cited to sample ~50–60 different parent bodies, a conclusion derived from the interpretation of the large number of ungrouped iron meteorites [4, 5]. Are these 50+ additional parent body samples from central metallic cores?

Additionally, recent work [6] has identified isotopic signatures in iron meteorites that suggest that they formed in two distinct reservoirs in the early Solar System: one with similarities to carbonaceous chondrites (CC-type) and the other with similarities to other meteorites (NC-type, noncarbonaceous). The two reservoirs have been proposed to be separated by Jupiter, thus representing inner and outer Solar System formation regions [6]. Do ungrouped irons sample more strongly one of these formation reservoirs over the other? Here I examine the chemical properties of ungrouped iron meteorites in comparison to established iron meteorite classifications to investigate these questions.

Results: The chemical compositions of iron meteorites are compared to chondritic values in Fig. 1. Of particular note is the striking difference between the distribution of NC-type and CC-type magmatic irons shown in Fig. 1D with respect to their Ir/Ni ratios; NC-types display a wide range of Ir/Ni values while Ir/Ni values of CC-types are more clustered and are higher than the chondritic Ir/Ni ratio. A higher level of refractory siderophile elements in CC-type iron was noted by [7] as consistent with an outer Solar System formation origin for these irons. Figure 1F shows that the distribution of Ir/Ni ratios in ungrouped irons is also fairly clustered, with a large fraction of the irons having Ir/Ni ratios higher than the chondritic value. I’ll discuss these similarities between CC-type and ungrouped irons, as well as other chemical observations, and the implications for the early Solar System cores sampled in our meteorite collections.


Figure 1. A comparison of the Ge and Ir concentrations in A. magmatic groups, B. non-magmatic groups, and C. ungrouped irons. D. Magmatic NC-type irons show considerably more variation in Ir than CC-type irons, E. non-magmatic irons, or F. ungrouped irons. Both magmatic CC-type and ungrouped irons have many samples with Ir/Ni ratios higher than chondritic values.
OXIDIZED PRIMITIVE ACHONDRITES SAMPLE DISTINCT PARENT BODIES. S. D. Crossley\textsuperscript{1}, R. D. Ash\textsuperscript{1}, J. M. Sunshine\textsuperscript{1}, T. J. McCoy\textsuperscript{2}, C. M. Corrigan\textsuperscript{2}, \textsuperscript{1}University of Maryland, Geology Department (8000 Regents Dr., College Park, MD, 20742, USA \texttt{sdcross@umd.edu}); \textsuperscript{2}Smithsonian Institution’s National Museum of Natural History, Washington, DC, 37012, USA.

Introduction: The brachinites are small group of FeO-rich, olivine-dominated meteorites (Fa\textsubscript{26-36}; 71-97 vol\%), often containing minor clinopyroxene (~\textsubscript{En}40-63 \textsubscript{Wo}36-48; up to 15 vol\%), with minor to trace amounts of plagioclase, orthopyroxene, Fe-sulfide, chromite, phosphates, and Fe-Ni metal [1]. Brachinites are traditionally classified according to their olivine abundance, composition, and O-isotopes, which span from \(\Delta^{17}\text{O} = -0.08\) to -0.39\%o [2]. Most authors consider the brachinites to be residues of partial melting of a chondritic precursor [e.g., 1,3], although there is evidence that some brachinites may have formed as cumulate rocks [4]. Such residual silicate record geochemical conditions during core formation, such as oxidation state [e.g., 2,5].

A number of ungrouped achondrites have been regarded as “brachinite-like” due to similar modal abundances (i.e., wherilitic), mineral compositions, and O-isotopes [2,6]. However, several of these oxidized ungrouped primitive achondrites were found to be anomalous in trace element contents [2], suggesting that they most likely formed in distinct parent bodies. Olivine in these ungrouped meteorites (~Fa\textsubscript{15-28}) also appears to be more reduced than in typical brachinites. The diversity of olivine-rich, primitive achondrites could be due either to different precursor materials or to distinct processes occurring in their respective parent bodies. We begin our study into this group by first examining the variety of precursor materials present in brachinites and similar ungrouped primitive achondrites, the relative redox conditions recorded during core formation, and how to distinguish the two groups in ways that reflect their formation.

Methods: Literature data was gathered for O-isotope, Fe-Mg-Mn, trace element systematics for brachinites and ungrouped samples [1-3,5-9, references therein]. We have added to literature through major element (Smithsonian, JSC) and trace element (UMD) examination of several brachinites and ungrouped samples.

Results and Discussion: Brachinites and ungrouped samples share a common range of O-isotopic ratios, but contain distinct olivine Fe/Mg. While most brachinites plot along a single redox trend in Fe-Mg-Mn space, several brachinites and ungrouped samples (AH 010, Brachina, NWA 3151, and NWA 4872) show clear signs of Mn loss during nebular processes, i.e., evaporation or condensation [10].

Brachinites generally show HSE abundances that are distinct from ungrouped samples [3]. Our examination of HSEs in RaS 309 shows relative HSE abundances that are typical for brachinites (Os/Ir >1). The relative abundance of HSEs in NWA 7297 are near-chondritic, which is more typical of the ungrouped samples. Due to HSE abundances and abundant metal and troilite, NWA 7297 may be more appropriately classified as an ungrouped achondrite, but is not a brachinite.

Plots of bulk Co/Ni versus Fe/Mg in olivine also serve to distinguish between brachinites and primitive oxidized wherellites. Co and Ni behave geochemically similarly during igneous processes, but Co becomes increasingly lithophile with oxidation [11], and Fe/Mg ratios in olivine increase correspondingly. Co/Ni ratios are higher for brachinites than ungrouped samples, but also extend over a greater range of Co/Ni values. Brachinites with the highest Co/Ni appear to have experienced more extensive extraction of Fe-Ni-S melts, as indicated by their lower modal abundance of metal/sulfides, while the more reduced ungrouped samples record lower Co/Ni possibly due to more limited Fe-Ni-S extraction and reducing conditions, as indicated by greater modal abundances of metal and troilite (up to 15 vol\%).

Conclusion: Brachinites and oxidized primitive achondrite precursors sampled multiple parent bodies, as indicated by Fe-Mg-Mn systematics. Ungrouped samples are consistently more reduced than brachinites, contain a greater abundance of metal and sulfides, and near-chondritic HSE ratios. Ungrouped samples are similar to brachinites, but formed under less oxidizing conditions and experienced less extensive Fe-Ni-S segregation.


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DIFFERENTIATION OF VESTA. V. Debaille¹, G. Hublet¹,², Q.-Z. Yin¹, J. Wimpenny³,⁴,¹Laboratoire G-Time, Universitë Libre de Bruxelles, Brussels, Belgium, vinciane.debaaille@ulb.ac.be, ²National Institute of Polar Research, Tachikawa, Japan, ³Department of Earth and Planetary Sciences, University of California at Davis, Davis, CA 95616, USA, ⁴Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.

Introduction: The HED (Howardite-Eucrite-Diogenite) meteorite series is now well accepted to originate from the asteroid 4-Vesta [1]. Eucrites are basaltic in composition, mainly made of Ca-poor and Ca-rich pyroxene and plagioclase, while diogenites are composed of Ca-poor pyroxene. By analogy with Earth, eucrites are usually thought to represent the vestan crust while diogenites would represent the mantle of the asteroid. However, age and geological relationships between those two families are not clear, with some studies having proposed that diogenites are younger than eucrites [2], or they could share the same age [3] or diogenites could even be older than eucrites [4, 5]. All studies also agree that Vesta differentiation was rapid, but available timing spans between ~3 million years (Ma) after CAI [6] up to more than 50 Ma after CAI using zircon dating [7].

In order to refine the chronology of the differentiation of Vesta, we have used the $^{26}$Al-$^{26}$Mg chronometer for dating 4 basaltic eucrites (Millbillillie, Camel Donga, Y-792510, Y-793591), 3 cumulate eucrites (A-881819, Y-980318 and Y-980433) and 3 diogenites (Bilanga, Johnstown and Tatahouine) [8].

Method: Preparation and chemical procedures were performed at the Université Libre de Bruxelles (ULB). Around 50 mg of each sample were used for bulk rock analyzes. Mineral separation was performed on ~200 to 500 mg coarsely crushed fractions of six eucrites (Camel Donga, Y-792510, Y-793591, Y-980433, Y-980318 and A-881819) and two diogenites (Bilanga and Johnstown) by using density separation and magnetic separation. After complete dissolution in 2:1 HNO₃/HF followed by two steps in concentrated HNO₃, an aliquot of 0.5% was taken for measuring $^{27}$Al/$^{24}$Mg ratios. Magnesium was purified by two steps using 1N HNO₃ and one step using a mixture of 1N HNO₃:0.1N HF. Mg isotopic ratios were measured on the HR-MC-ICP-MS NuPlasma at the ULB using an Aridus 2 desolvating nebulizer. Some Mg isootope data were also collected using the new HR-MC-ICP-MS NuPlasma II at ULB and an Apex desolvating nebulizer and the measurements of some eucrites were replicated using a Thermo Neptune MC-ICP-MS at University of California in Davis (UC Davis). The deviation from the reference terrestrial value is noted $\delta^{26}$Mg*, and is expressed as:

$$\delta^{26}\text{Mg}^* = \delta^{26}\text{Mg} - [(1 + 0.001 \times \delta^{25}\text{Mg})^{1/0.511} - 1] \times 1000$$

Results and discussion: All basaltic eucrites except Y-793591 present a fully resolvable excess in $\delta^{26}$Mg* from the terrestrial standard (0.005 ± 0.009). On the contrary, cumulate eucrites have a value of $\delta^{26}$Mg* (0.010 ± 0.003 to 0.021 ± 0.016) close to or within the terrestrial range, and the $\delta^{26}$Mg* values of diogenites are within the terrestrial range [8]. We observe that despite all the samples could plot together on a planetary isochron, the robustness of the isochron increases when only basaltic eucrites are considered, giving an age for the formation of the vestan crust of 2.66$^{+0.39}_{-0.58}$ after CAI. This age is consistent with the individual age obtained on mineral separates of Camel Donga and Y-793591, but not Y-792510 (6.75$^{+0.25}_{-0.66}$ Ma). Since that basaltic eucrite is highly metamorphosed, its younger age likely reflects metamorphic resetting due to impact when $^{26}$Al was extant. The ages obtained for cumulate eucrites by internal isochrons span from 5.48$^{+1.58}_{-0.60}$ Ma to >7.25 Ma after CAI, thus resolvably younger than the WR basaltic eucrite age [8].

Diogenites studied here, despite having a non-chondritic $^{27}$Al/$^{26}$Mg ratio, have no anomaly in $\delta^{26}$Mg* that would normally be expected if these objects were formed while $^{26}$Al was extant. We interpret this as diogenites being formed after the complete extinction of $^{26}$Al by late remelting of the vestan mantle, possibly related to a mantle overturn, and as such, they intruded the eucritic crust [2]. Model ages indicate that basaltic and cumulate eucrites share a common source that differentiated 2.88$^{+0.14}_{-0.12}$ Ma after CAI, i.e. contemporaneously of the crust emplacement as evidenced by basaltic eucrites [8]. No model age is obtained for diogenites, corroborating they represent a mixture between their magma parent and the eucritic crust [2].

The $^{26}$Al-$^{26}$Mg systematics of eucrites indicate that Vesta differentiated very rapidly from a chondritic precursor within the first 3 Ma after CAI, consistent with the Hf-W systematics [6]. The eucritic crust was emplaced concomitantly by extrusive magmatic activity. The deeper part of the crust sampled by cumulative eucrites underwent slow cooling up to several Ma later.

Several new developments in astrophysical modeling and solar system observations have changed the way we think about the accretion and differentiation of terrestrial planets. Planetary embryos are now widely recognized to have formed very rapidly and early in the disk’s evolution. Marking time zero with formation of Ca-rich, Al-rich inclusions (CAIs), Mars appears to have formed and undergone core-mantle differentiation largely by about 1.9 Myr, based on Hf-W [1] and \(^{60}\text{Fe-Fe}\) radiometric dating of martian meteorites. Stable isotope trends among planetary bodies strongly suggest that Jupiter’s 20-30 Me core formed only ~0.4 - 0.9 Myr after CAIs [3].

New astrophysical models explain how planets can form so rapidly. Streaming instabilities [4,5] can allow ~10 cm-sized solids (e.g., aggregates of dust-shrouded chondrules [6]) to quickly (few orbits) assemble into planetesimal-sized bodies with a power-law distribution of sizes up to ~100 km, consistent with bodies in the asteroid belt and Kuiper belt. The main requirements are a modest enhancement in solids-to-gas ratio above average, and particles with sizes within a broad range. Once a population of > 100- km planetesimals forms (probably by merger of ~100-km planetesimals), they form the seeds for rapid growth to planetary embryos by pebble accretion [6,7]. Growth to planetary embryo scales (Moon- to Mars-mass) in the inner solar system is predicted to be very rapid, less than about 10\(^6\) yr. In the outer solar system, growth to several Earth masses is possible in < 1 Myr [3,6].

Faster accretion times allow for greater heating. The gravitational potential energy per mass of 0.01 – 0.1 Me embryos is 1.5 – 7.0 x 10\(^6\) J/kg. accretion of bodies a time \(t\) after CAIs with canonical ratio \(^{26}\text{Al} / ^{27}\text{Al} = 5 \times 10^{-5}\) leads to 6.8 x 10\(^6\) J/kg \(\exp(-t / 1.03\) Myr) heating. accretion of embryos at 1 Myr yields a significant 2.6 x 10\(^6\) J/kg of radiogenic heating.

Earth and Venus very likely grew from accretion of already differentiated Moon- to Mars-sized embryos, implying siderophile elements partitioned into cores under conditions pertinent to bodies smaller than Earth. Further equilibration with Earth’s mantle would be possible only if merger of cores was incomplete [8].

More importantly, some embryos grew to sizes large enough to accrete significant atmospheres while nebular gas was still present. The solar nebula likely persisted for several Myr [9]. Embryos growing to 0.1–0.3 Me in that time would accrete up to ~0.1 bar H\(_2\)/He atmospheres [10] that could persist long after the nebula dissipated, helping insulate long-lived magma oceans [11,12], offering opportunities to ingas H\(_2\), H\(_2\)O or noble gases into the planet’s mantle [13], and/or enhanced volatile loss [12]. Ingassed species such as low-D/H hydrogen observed in some deep-mantle samples [14], may trace magma ocean crystallization and overturn and/or core formation.

Besides advances on terrestrial planet accretion and differentiation, our understanding of how Kuiper belt objects (KBOs) accrete and differentiate has improved. Growth by streaming instability and pebble accretion as in the asteroid belt seems to apply to the Kuiper belt as well, and the difference in asteroid and KBO size distributions helps constrain the process [6]. Thermal models of KBOs suggest rock-ice separation is incomplete if they accrete slowly (> 10\(^6\) yr), leaving thick, undifferentiated rock-ice crusts [15]; but in cases like Charon, which accreted quickly (< 10\(^3\) yr), accretional heating probably helped complete rock-ice separation [16]. Rocky cores in all small icy bodies should experience extensive hydrothermal circulation and water-rock interactions [17], evidence for which exists in possible KBO Ceres [18], and the KBO Haumea [19].
CONSTRAINING THE TIMING OF THE VESTAN DYNAMO. S. Dey, M. Huyskens, M. E. Sanborn, J. A. Tarduno, and Q.-Z. Yin. *Department of Earth and Planetary Sciences, University of California at Davis, Davis, CA 95616 (qyin@ucdavis.edu), Department of Earth & Environmental Sciences, University of Rochester, Rochester, NY 14627*

**Introduction:** Characterization of paleomagnetic fields of differentiated meteorites provides fundamental information on dynamo processes and thermal evolution on small bodies in the early solar system. Recent advances in paleomagnetic studies of meteorites have revealed strong paleofields requiring past dynamos in several asteroids, including angrites [1], pallasites [2], and the Howardite-Eucrite-Diogenite (HED) parent bodies [3], with the latter being most likely the asteroid 4 Vesta [4]. Solar and nebular fields could not be a source of these magnetization, because they should have dissipated within the first ~6 Ma of solar system formation [5]. However, the current evidence [3] for Vesta dynamo is indirect. It was inferred that a shock melted meteorite, ALHA 81001, which was interpreted to have cooled 3.69 billion years ago in the presence of a small field created by nearby crust that itself was magnetized in an ancient field while a dynamo was active [3].

Clearly, a direct reading of magnetic field strength of Vesta is needed. Diogenites are widely regarded as deep-seated rocks, magma ocean cumulates and/or crustal intrusive bodies of 4 Vesta [7], although harzburgitic and dunitic diogenites are also known [8]. Northwest Africa (NWA) 5480 is an olivine-rich diogenite (olivine-diogenite or harzburgite) with 57 vol.% and 42 vol.% olivine and orthopyroxene, respectively [8]. It is a pristine, low shock, unweathered rock. Its petrology and geochemistry has been studied in detail [e.g. 8,9]. Preliminary paleointensity data shows that NWA 5480 preserves a strong magnetic field of approximately 36 μT [10]. This implies a Vesta dynamo as the primary source since alternative sources are not expected to impart such a strong field [10]. Moreover, based on microstructural and fabric analysis of olivine and pyroxene grains it was inferred that NWA 5480 has undergone solid-state plastic deformation post-crystallization [11]. Observing plastic deformation is strong evidence that this diogenite recorded dynamic mantle convection occurring in the parent body 4 Vesta [11]. Olivine banding observed in this rock has been interpreted as evidence for magmatic flow in the mantle of 4 Vesta [8]. These features make NWA 5480 a particularly interesting rock as it may preserve a signal of past mantle convection.

While the presence of magnetized Vesta rocks implies it had solidified and cooled to below the Curie temperature during the presence of an early active dynamo [3, 10], it does present a thermal paradox for Vesta. If the current 26Al-26Mg age interpretations for diogenites are correct [12], early 26Al decay results in a mantle initially hotter than the core, potentially inhibiting dynamo generation. All thermal models exclude such an early dynamo [13,14]. Therefore, constraining the age of diogenites in general, and NWA 5480 in particular, is of critical importance for better understanding the temporal context of dynamic mantle processes and the formation of core dynamo in the asteroid 4 Vesta.

We have recently applied the short-lived 55Mn-53Cr isotope system to constrain the timing of formation of NWA 5480 to be ≤ 4547.64 Ma [15], i.e., after > 19.68 Myr since the beginning of the solar system [15]. We additionally, used the observed isotopic anomalies in the stable 54Cr isotope to investigate its relationship to other HEDs [15]. Here we explore U-Pb isotope systematics of NWA 5480 in order to further constrain its absolute age.

**Results and Discussions:** For an asteroidal dynamo to be active and generating magnetic fields that can be recorded in differentiated meteoritic minerals, a Goldilocks window of timing must be satisfied. (1) It must not be too early when heating from 26Al (half-life = 0.73 Myr) results in a silicate mantle hotter than the metallic core and (2) It must also not be too late such that the metallic core has fully crystallized causing the dynamo to cease. Our new Mn-Cr age [15] and Pb-Pb age (to be reported at the meeting) imply that when NWA 5480 crystallized, 26Al must have been completely decayed away. Together with the magnetic data [10] our new age also suggests that heat may have been removed by the Vesta silicate mantle by early convection, consistent with the plastic deformation observed in NWA 5480 [11].

AN EXPERIMENTAL ANALOG FOR METAL-SULFIDE PARTITIONING IN ACAPULCOITE-LODRANITE METEORITES. J. K. Dhaliwal¹, N. L. Chabot², R. D. Ash³ and T.J. McCoy⁴. ¹Dept. of Geosciences, Pennsylvania State University, University Park, PA (jkdhalival@psu.edu) ²Johns Hopkins University Applied Physics Laboratory, Laurel, MD. ³Dept. Of Geology, University of Maryland, College Park, MD, ⁴Dept. of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC.

Introduction: The primitive achondrites are a unique and valuable class of meteorites that are partially differentiated and reflect early metal-sulfide segregation in planetesimals in our Solar System. These meteorites include the ureilites, brachinites and acapulcoite-lodranites; recent work on highly siderophile element (HSE: Re, Os, Ir, Ru, Pt, Pd) relative abundances in these samples show unusual partitioning of Pt and Pd [1-3]. These studies suggest that the inter-element fractionation among the HSE can be described by solid metal-liquid metal partitioning in the presence of sulfur [4]. The present study builds on this prior work, and seeks to replicate this HSE partitioning through high temperature melting experiments of naturally occurring metal and troilite separates.

Methods: The experiments were conducted at the John Hopkins University Applied Physics Laboratory (APL) using previously established techniques for investigating trace-element partitioning in solid metal-liquid metal systems [e.g., 5]. The major difference between this study and prior work was the use of natural materials; FeNi and FeS aliquots were isolated from the IAB iron meteorite, Mundrabilla (courtesy of the Smithsonian), and placed adjacent to each other in silica glass tubes for each experiment. The experimental set-up consisted of eight runs at 1 bar pressure: (1) 1100°C for 1 hr; (2) 1100°C for 16 hrs; (3) 1000°C for 1 hr; (4) 1000°C for 15 hrs; (5) 1100°C for 30 min; (6) 1100°C for 15 min; (7) 1100°C for 7 min; (8) 950°C for 1 hr.

Results: Petrography: At all temperatures, there is incipient metal-melting, evident in the rounded edges of FeNi along the edges at the interface with FeS. The quenched liquid metal phase has a dendritic texture for higher temperatures, 1000°C and 1100°C, and longer durations (1 hour and overnight). This texture is similar to prior solid metal-liquid metal experiments [e.g., 6], and becomes progressively less dendritic with shorter durations. In the experimental runs at 1100°C for 7 min, the quenched material is suggestive of an interstitial sulfur-rich material (Fig. 1a).

Geochemical Analyses: The Mundrabilla meteorite contains both kamacite and taenite phases, with an average Ni content of 8.3 ± 2.2 wt.% in bulk solid metal grains (measured using an Hitachi 300 TM benchtop SEM at APL). In the experimental melts, the deformed solid FeNi at the interface with the melted FeS has a noticeably lower Ni content, with a range of 3.3 to 8.3 wt.%. The interstitial material has variable Ni content, ranging from negligible to as much as 5.7 wt. %. Because Ni should be excluded from sulfur-rich phases, this indicates the presence of fine-grained FeNi, which is not distinguishable at 1500x magnification (Fig. 1a).

Discussion: The results of this study can help understand metal-sulfide partitioning that may have occurred on the acapulcoite-lodranite parent body. This is evident in the petrographic similarity between metal melting and pooling between experimental melts and the transitional acapulcoite-lodranite, EET 84302 (Fig. 1). The variable Ni content of the melted metal and interstitial phases suggests that siderophile contents are affected by sulfur interactions with the melting metal; this may be analogous to the decrease in Pt/Os and Pd/Os ratios observed for acapulcoite-lodranite meteorites with decreasing sulfur contents [3].

We have conducted in situ laser ablation-inductively coupled plasma mass spectrometer (LA-ICPMS) analyses of HSE of these experiments at University of Maryland and will present these results. These HSE partitioning results will provide insight into how these experiments approximate the conditions of very early metal-sulfide partitioning on the parent bodies of primitive achondrites.

A REVIEW OF EXPERIMENTAL STUDIES SIMULATING LUNAR MAGMA OCEAN SOLIDIFICATION. D. S. Draper¹ and T. C. Prissel². ¹Astromaterials Research Office. NASA Johnson Space Center, 2101 NASA Parkway, Mail Code XI3, Houston TX 77058, david.draper@nasa.gov. ²Department of Earth & Planetary Sciences, Rutgers University, 610 Taylor Rd., Piscataway, NJ 08854.

Introduction: Lunar magma ocean (LMO) crystallization is a guiding paradigm for understanding the thermal and magmatic evolution of the Moon. Important inferences arose from numerical crystallization models [1, 2], and more recently, petrologic experiments duplicating the entire process of LMO solidification. The experiments provide extensive, internally-consistent datasets that cover the likely range of LMO compositions and crystallization histories, enable important inferences about lunar evolution, and provide needed inputs to numerical LMO models and understanding of post-LMO magmatism. Here we review key aspects of and results from these experiments.

Types of crystallization, range of starting compositions: Some studies (e.g. [3-5]) experimentally simulated the numerical model of [1], which features initial equilibrium crystallization followed by fractional crystallization of the LMO. Others simulated fractional crystallization operating from the outset of solidification (e.g. [6-8]) as suggested by later models (e.g. [2]). Compositions used include Taylor Whole Moon (TWM) [9], with ~6 wt% Al₂O₃ and Mg# = 84; a depleted Lunar Primitive Upper Mantle (LPUM) [10,11] with ~4 wt% Al₂O₃ and Mg# = 90; and a composition derived via inversion of lunar seismic data [12] with 4.5 wt% Al₂O₃ and Mg# = 86. TWM includes an enrichment of ~50% in refractory elements (e.g. Al, Th) relative to Earth [13], whereas LPUM represents no refractory element enrichment. The Snyder model [1] used a composition with 5 wt.% Al₂O₃ and Mg# 82.

Summary of results: Whether a two-stage or fully fractional process, LMO crystallization produces cumulate piles (Fig. 1) with denser, more Fe-rich material at the top and less dense, more magnesian material at the base. Thus cumulate overturn is likely, as predicted by numerical models. Reconciling these results with the production of a plagioclase-rich crust of similar thickness to that inferred by the GRAIL mission [14] is complicated by uncertainties in bulk solar Na₂O and water contents (not every experimental or numerical study included Na₂O, and only Lin et al. [4, 5] set out to evaluate its role). Experimentally-determined residual liquids show broad similarities with the Snyder [1] model for MgO and Mg#, and less so for TiO₂ contents. In contrast, measured SiO₂ and Al₂O₃ decrease with crystallization instead of increasing as predicted, and vice versa for CaO and FeO. The last liquids produced have many features that have been ascribed to KREEP, both in terms of phase equilibria and major element contents, and with respect to REE contents inferred from applying relevant partitioning data. These results provide a springboard for future, more focused experimental and numerical simulations of LMO crystallization.

CHRONOLOGY OF PLANETESIMAL DIFFERENTIATION BASED ON TIMING OF ACHONDRITE FORMATION IN THE EARLY SOLAR SYSTEM. D. R. Dunlap¹ and M. Wadhwa², ¹²Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe AZ 85287. drdunlap@asu.edu

Introduction: Achondrites are igneous rocks which record the earliest epoch of planetesimal melting and differentiation [1]. Studying the chronology of achondrites is vital to understanding the timeline of accretion, differentiation, and subsequent reheating of planetesimals [2]. We present here a status report of an ongoing project to constrain the high resolution chronology of igneous processes on a variety of achondrite parent bodies.

Samples and Methods: Thus far, we have investigated the high resolution chronologies of 1) 2 primitive achondrites, the brachinites Brachina Northwest Africa (NWA) 4882, 2) 2 eucrites, Juvinas and NWA 10919, and 2 anomalous eucrites, NWA 4470 and Sayh al Uhaymir (SaU) 493, and 3) 2 ungrouped differentiated achondrites, NWA 7325 and NWA 11119. We have applied several high precision chronometric techniques (including Al-Mg, Mn-Cr and Pb-Pb) to these achondrites; analytical details can be found in recent abstracts and papers referenced throughout this abstract.

Discussion: Ages obtained with different chronometers on various achondrites will be discussed in terms of the crystallization ages representing formation times, model ages representing the timing of silicate fractionation/partial melting on the parent bodies (these typically make the assumption of a chondritic parent body composition), and resetting (or upper limit on) ages where the chronometer was reset by a later heating (possibly impact) event.

Primitive Achondrites: Investigations of the $^{53}\text{Mn}-^{53}\text{Cr}$ systematics of two Brachinites (Brachina and NWA 4882) reveal that Brachina has an ancient crystallization age of 4564.8 ± 0.3 Ma [3] while NWA 4882 is ~15 Ma younger [4]. This indicates that the Brachinite parent body experienced a prolonged thermal history. The $^{26}\text{Al}-^{26}\text{Mg}$ model ages for these brachinites indicate that partial melt removal occurred at ~4567 Ma [5] on their parent body. The younger $^{53}\text{Mn}-^{53}\text{Cr}$ age of NWA 4882 likely resulted from late thermal metamorphism.

Eucrites: The eucrites Juvinas and NWA 10919 as well as the anomalous eucrite NWA 4470 and the ungrouped achondrite SaU 493 (which we consider to be an anomalous eucrite; [6]) have been investigated using $^{26}\text{Al}-^{26}\text{Mg}$ systematics. All four these samples have equilibrated $^{26}\text{Al}-^{26}\text{Mg}$ systematics and as such, only provide upper limits of ≤ 4561 Ma on their formation/equilibration times. [5,7,8]. On the Euclidean parent body, this equilibration is likely the result of thermal metamorphism resulting from a large impact. The weighted mean $^{26}\text{Al}-^{26}\text{Mg}$ model age for these samples is 4565 ± 1 Ma indicating that silicate differentiation occurred early and concurrently on their parent body(ies). These results agree with the findings of [9].

Ungrouped Differentiated Achondrites: The NWA 7325 and NWA 11119 ungrouped achondrites have compositions quite distinct from other known types of achondrites. Their mass-independent O and Cr isotope compositions indicate that they likely originated on a common parent body [10,11]. The $^{26}\text{Al}-^{26}\text{Mg}$ and Pb-Pb ages of NWA 7325 are concordant and give a crystallization age of ~4563 Ma [8,12]. The $^{26}\text{Al}-^{26}\text{Mg}$ and Pb-Pb ages of NWA 11119 are also concordant and give a crystallization age of ~4564 Ma [10,13]. NWA 11119 has a unique anodesite-dacite bulk composition and has the most amount of free silica of any known achondrite [10]. The fact that this evolved crustal rock was forming so early (within ~3 Ma of CAIs [14]) has important implications for our understanding of crustal processing on planetesimals in the early Solar System.

Summary: The findings discussed here provide critical constraints on the differentiation and subsequent evolution of achondrite parent bodies in the early Solar System. Accretion and melting of various planetesimals began almost contemporaneously with CAI formation, and crystallization of crustal rocks followed within ~3 Ma of CAIs. Evolved, high-silica crustal compositions are possible on some planetesimals and their formation occurred concurrently with the earliest basaltic crusts. Thermal metamorphism (most likely from impact heating) caused prolonged thermal histories that spanned up to ~20 Ma after parent body accretion.

**Introduction:** The Mg-suite is a series of ancient plutonic rocks from the lunar crust with ages and compositions indicating that they represent the first post-differentiation crust-building magmatism [1, 2]. Samples of Mg-suite materials were found at every Apollo landing site except 11 and all exhibit geochemical characteristics indicating the involvement of KREEP in their petrogenesis [3-5]. This has led to the suggestion that the KREEP reservoir under the nearside was responsible for Mg-suite magmatism [e.g., 5, 6]. The lack of readily identifiable Mg-suite rocks in meteoritic regolith breccias sourced from outside the Procellarum KREEP Terrane (PKT) seemingly supports this interpretation.

One attractive aspect of including KREEP as a necessary component of Mg-suite formation models is the high abundance of heat-producing elements in KREEP (e.g., K, Th). The primitive major element compositions of Mg-suite rocks indicate mantle source rocks with high melting temperatures, so KREEP presents a convenient heat source for Mg-suite magmatism inside the PKT [5, 6]. However, given that Mg-suite ages are essentially identical to both FANs and models ages for KREEP and mare basalt sources [7], there may not have been sufficient time for radiogenic heat to accumulate and significantly impact the onset of Mg-suite magmatism. Here, we propose an alternative model by which the presence of KREEP can affect Mg-suite melt production: melting point depression. We have undertaken high-temperature experiments to test the model that KREEP resulted in melting point depression of FAN-early LMO cumulate source materials. Additionally, we are currently performing calculations to test the radiogenic heating model to better constraint the relative contributions of melting point depression and radiogenic heating to Mg-suite melt production.

**Experimental Design:** Six starting materials with 0%, 5%, 10%, 15%, 25%, and 50% of the KREEP mix by weight were prepared by combining a synthetic KREEP composition [8] with a 50:50 mixture of powdered San Carlos olivine and powdered Miyake-jima anorthite, which are compositional analogs for deep mantle dunites and FANs. Experiments were conducted in a Deltech vertical gas mixing furnace at the Geophysical Lab at an \( f_{\text{O}_2} \) corresponding to the IW buffer using a CO-CO\(_2\) mixture. Experiments were soaked for 4 – 6 days to ensure a close approach to equilibrium.

**Discussion:** Our experimental results demonstrate that the addition of KREEP to a mixture of crustal anorthosite and deep mantle dunite, which is the likeliest source rock for the Mg-suite [1, 5], depresses the melting temperature relative to a KREEP-free source. To assess the degree of this effect, we consider only melting experiments saturated in olivine and plagioclase, but not low-Ca pyroxene. These magmas would produce primitive troctolites. Our experiments show that the addition of 5% - 50% KREEP in the source rocks results in an increase in melt production by a factor of 2x – 13x over a KREEP-free source. The melts are in equilibrium with olivine and plagioclase with An#s and Mg#s similar to Mg-suite troctolites, showing that even with the addition of 50% KREEP, major element constraints are not violated. Trace elements provide additional constraints on our model. We calculated the REE abundances in our experimental melts using trace element partitioning parameterizations for olivine and plagioclase. We also modeled the REE abundances of Mg-suite parental magmas. In all cases, REEs in our experimental melts are slightly lower than or similar to troctolite parental magmas.

We are currently performing calculations to determine the temperature increases that would be expected in source regions with the same percentages of KREEP as our experiments. The short time intervals between KREEP formation and the onset of Mg-suite magmatism combined with heat loss due to cooling may affect the ability of radiogenic heating to be the driver for Mg-suite magmatism.

These findings strongly suggest that KREEP-induced melting point depression could have had a significant impact on Mg-suite melt production on the nearside vs. farside. Our findings do not preclude the occurrence of Mg-suite magmatism in the farside crust, but demonstrate that models of Mg-suite petrogenesis should predict far more magmatism on the nearside, perhaps by an order of magnitude or more. This conclusion is independent of the effects of any radiogenic heat production from KREEP.

**References:**
Introduction: High-precision analyses of Fe stable isotope ratios in planetary materials have revealed significant variations among the currently sampled planets and asteroids. Some workers have argued that a heavy terrestrial mantle (δ57Fe of roughly 0.10‰) and the heavy average δ57Fe of lunar basalts are representative of light isotope loss during the Giant Impact [1, 2] or via volatile depletion [3] during accretion. The disproportionate of Fe2+ by bridgmanite in Earth’s deep mantle can also cause heavy isotope enrichment in the mantle [4]. However, a heavy mantle is not the community consensus, as the average δ57Fe of the global peridotite suite in chondritic [5]. We have previously shown that low pressure core formation leads to light Fe isotope enrichment in planetary mantles [6, 7], scaling with the amount of S and/or Ni in the core. Here we investigate the effects of Si in cores on Fe isotopic fractionation using high-P-T experiments to simulate low-P core formation and density functional theory (DFT) calculations for high-P terrestrial core formation.

Experimental and Analytical Methods: High-P-T experiments were conducted in a piston cylinder at the Geophysical Laboratory (GL). A model peridotite composition was mixed with nominal metal compositions of Fe93Si7 and Fe95.5Si14.5. Starting materials were spiked with 54Fe, such that the three-isotope exchange method could be used to assess isotopic equilibrium, and placed inside graphite capsules. All experiments were conducted at 1 GPa and 1850 °C for between 30 mins to 3 hours, sufficient time to achieve isotopic equilibrium [6, 7]. The compositions of Fe-Si alloys and quenched melts were analyzed using the fully quantitative silicon-drift detector EDS on the JEOL 6500 field-emission SEM at GL. Metal and silicate fractions were dissolved in concentrated acids and Fe was purified from matrix elements. Isotopic compositions were determined using MC-ICP-MS at GL.

Density Functional Theory: Theoretical beta-factors used to calculate the mass dependent iron isotope fractionation were estimated using the standard thermodynamic approach as obtained from phonon integration in crystalline materials. These calculations were made using density functional perturbation theory in the ABINIT implementation. Full details on these calculation methods can be found in Shahar et al. [8].

Results: Our experiments resulted in Fe-Si-C alloys containing between 1.3 and 8.1 at. % Si. The Δ57FeCore-Mantle (i.e., δ57FeMetal - δ57FeSilicate) values for these experiments are generally consistent with our previous results for S- and Ni-bearing Fe alloys [6, 7]. The results of DFT calculations for Fe metal show that at pressures of 40 and 80 GPa, the Δ57FeMetal-Bridgmanite is negative. The Δ57FeMetal-Bridgmanite for FeSi at 80 GPa is positive and roughly a factor of two greater in magnitude than for Fe metal.

Interpretations: Our experimental results suggest that Si entering planetary cores at low pressure may have a similar effect to Ni and S. The Δ57FeCore-Mantle at 1850 °C of the experiment containing the most Si-rich metal is the highest among our Si-bearing experiments and falls close to the trend in the Ni- and S-bearing experiments. This would be consistent with the model suggested by Elardo and Shahar [7] wherein elements that substitute for Fe in the alloy structure result in a metal-silicate isotope fractionation, whereas elements such as C that partition into interstitial sites do not have a resolvable effect at 1850 °C. However, it is difficult to draw any definitive conclusions from this dataset because all of the Si-bearing experiments have Δ32FeCore-Mantle values at 1850 °C within analytical error of 0‰. Experiments with greater amount of Si in the metal phase are needed, but are extremely challenging due to reduction of FeO to Fe metal by Si metal.

Shahar et al. [8] showed that at high pressure Fe isotope fractionation between bridgmanite and Fe metal, Fe,C, FeHx and FeO results in the silicate becoming heavier than the Fe alloy. Our DFT results show that FeSi has the opposite effect, indicating that Si entering the core at high pressure conditions would enrich the mantle in light Fe. FeSi is an end-member phase; however it indicates the sign of the metal-silicate fractionation factor for Si-bearing Fe alloys would be positive. Our calculations indicate that the presence of Si in the core would be inconsistent with the supposition that the δ57Fe of the bulk silicate Earth is heavy with respect to chondrites.

WHAT CAN THE Hf–W SYSTEM TELL US ABOUT THE MECHANISM AND TIMING OF EARTH’S CORE FORMATION? R. A. Fischer¹, F. Nimmo², and D. P. O’Brien³, ¹Harvard University, ²University of California Santa Cruz, ³Lunar and Planetary Institute.

Introduction: The Hf–W isotopic system is one of the most widely used geochemical tools for dating Earth’s core formation [e.g., 1]. $^{182}$Hf decays into $^{182}$W with a half-life of 8.9 Ma [e.g., 2]. During core formation, moderately siderophile W is mostly sequestered into the core. If lithophile $^{182}$Hf is alive during core formation, it will remain in the mantle and decay into $^{182}$W, creating an excess of $^{182}$W relative to other W isotopes. Previous studies show that the Hf–W system is also sensitive to the siderophility of W and the degree of metal–silicate equilibration [e.g., 3–5].

Here we use Hf–W modeling to investigate the core formation process. Relative to previous Hf–W models, we introduce several novel concepts. First, the partitioning behavior of W varies with pressure ($P$), temperature ($T$), oxygen fugacity ($f_{O_2}$), and composition ($X$) as the Earth grows. Second, a large number of accretion simulations are used, to illustrate how stochastic variability in growth history affects the Hf–W system. Finally, we incorporate a full core formation model, so Earth’s mantle composition provides additional constraints.

Methods: Growth histories for 73 Earth analogues are taken from 100 N-body simulations [6], fifty with Jupiter and Saturn on initially circular orbits (CJS) as predicted by the Nice model and fifty with Jupiter and Saturn on their current, eccentric orbits (EJS). We are currently undertaking calculations using 16 Grand Tack simulations [7].

The output of these simulations is combined with a core differentiation model [8], in which bodies undergo $P$-$T$-dependent metal–silicate equilibration with each impact. Many major, minor, and trace elements are tracked, and $f_{O_2}$ is evolved self-consistently [9]. W partitioning as a function of $P$-$T$-$f_{O_2}$-$X$ is based on [10]. Between impacts, radiogenic $^{182}$W is produced in the mantle, and with each impact, the $^{182}$W abundance is modified by a core formation event. Adjustable parameters include the equilibration depth ($P$-$T$), amounts of metal and silicate equilibrating, thermal profile, and initial $f_{O_2}$.

Results and Discussion: In the first few 10s of Ma, the tungsten anomalies ($ε^{182}$W) reach a few hundred due to the very siderophile behavior of W at low $P$-$T$ and Earth-like $f_{O_2}$, an effect not seen in previous studies that used a constant W partition coefficient.

The degree of equilibration cannot be varied in isolation, because doing so affects other aspects of planetary chemistry (e.g., mantle W abundance) [8]; here a compensating change in equilibration depth is used to maintain an Earth-like mantle composition. Reducing the degree of equilibration increases the final tungsten anomaly [e.g., 11] (Figure). For whole mantle equilibration, Earth’s anomaly is best matched with the fraction of equilibrating metal $k = 0.4$, in agreement with previous studies [12–13]. Matches are also achieved for $k = 0.55$ and equilibration with 5x the impactor’s silicate mass, or $k = 1$ and 3x the impactor’s silicate mass, or some intermediate combination (Figure).

These N-body simulations produce Moon-formation ages (last giant impact times) of 10–175 Ma. Later final impacts require less equilibration to match Earth’s tungsten anomaly. For whole mantle equilibration, final impacts at ~50 Ma require $k = 0.4–0.55$; those at >150 Ma require $k = 0.25–0.4$. For the right combination of model parameters, nearly all Earth analogues can have the observed anomaly regardless of formation timescale. Requiring a small late veneer generally excludes last impact dates of <65 Ma [6, 14]. At these later times, matching Earth’s anomaly requires $k = 0.2–0.55$ regardless of equilibrating silicate mass, implying equilibration depths of 0.5–0.7x the core–mantle boundary pressure. There are strong tradeoffs between $k$, equilibrating silicate mass, depth, and timing of core formation, underscoring the importance of understanding the physical processes that control metal–silicate equilibration.

SIDEROPHILE ELEMENT FRACTIONATION IN METAL IN UREILITES: CHALLENGING THE DEFINITION OF PRIMITIVE ACHONDRITES. C.A. Goodrich, Lunar and Planetary Institute, USRA, 3600 Bay Area Blvd., Houston, TX 77058 USA. goodrich@lpi.usra.edu

Introduction: Primitive achondrites are considered to be transitional between primitive, undifferentiated chondrites and fully differentiated nonchondrites [1-3]. Their parent asteroids may have melted and experienced partial differentiation, but they did not experience large scale separation into core, mantle and crust, and their primary isotopic and chemical heterogeneities were not completely erased [4,5]. The acapulcoite-lodranites are the quintessential primitive achondrites, with a range of properties that reflect various degrees of melting and melt separation [6-9]. Other nonchondrites that have been classified as primitive achondrites by some authors are winonaites-IAB-IIICD iron meteorites, brachinites, and ureilites [1,3,8].

The ureilites, however, do not conform to the primitive achondrite paradigm [2]. Although they show higher degrees of silicate melt extraction (complete removal of the basaltic component) than acapulcoite-lodranites (or other primitive achondrites), and thus should show the highest degree of $\Delta^{17}$O homogeneity, they actually show the least (range of $\Delta^{17}$O = ~2‰ compared with ~0.4‰ among acapulcoite-lodranites) [4,5]. [10,11] argued that pre-igneous $\Delta^{17}$O heterogeneity among ureilites was preserved due to rapid, fractional extraction of silicate melts. However, [12] argued that efficient extraction of silicate melt from asteroidal mantles would be inhibited by the failure of earlier-formed metallic (Fe+S) melts to segregate from the silicates. I use siderophile element abundances in ureilite metal to address this problem.

Siderophile Elements in Ureilite Metal: Ureilites contain ~1-3% kamacite as strips along silicate grain boundaries. CI-normalized abundances of Os in this metal range from ~2 to 65 (among ureilites) and are correlated with increasing Os/Pt, Os/Ni and Os/Pd ratios [16]. The most fractionated patterns have CI-normalized Pt/Os ~0.3 and Pd/Os ~0.06, which is significantly more fractionated than metal in lodranites (Pt/Os ~0.52, Pd/Os ~0.24 [9]). Several authors have noted that, to first order, siderophile element abundances in ureilites correlate with D(solid metal/liquid metal) in the Fe(Ni)-S system, and thus argued that ureilites experienced partial melting of metal with loss of a S-rich melt [13-15]. Those studies were based on bulk siderophile element abundances. In contrast, [16] modeled melting and separation of metal using siderophile elements in the metal itself, which eliminates uncertainties introduced by loss of metal in terrestrial weathering, and adds the critical constraint of elemental abundances in addition to ratios. Calculations of [16] showed that the large fractionations of HSE observed in metal in most ureilites require extremely high degrees (>98%) of batch Fe-S melt extraction, which implies very high $x_{FeS} (= \text{wt.} \text{FeS}/[\text{Fe+FeS}])$ in the precursor material. Furthermore, at such high degrees of fractionation, the HSE are so strongly concentrated into the residual metal that to match their relatively low absolute abundances in ureilite metal, high initial metal contents are required. Together, these constraints imply ureilite precursors with abundances of Fe metal and FeS (~20-35 wt.% each) that far exceed those of CC or OC. [16] considered this implausible, and suggested non-chondritic initial siderophile element ratios instead.

Discussion: The conclusion of [12] that efficient extraction of silicate melts would be inhibited by the inability of early Fe+S melts to segregate was based on metal and S abundances for Vesta. Those authors pointed out that segregation of metallic melt before the onset of silicate melting was only possible if the liquid metal phase exceeded ~5 vol.%, which it would not have for Vesta. However, the very high metal and sulfide abundances inferred for ureilite precursors [16] could result in this requirement being met. For example, for an initial Fe+FeS content of 65 wt.%, with $x_{FeS}$ ~0.54 (which can lead to the most fractionated ureilite metal), ~50 wt.% of the metal phase, or >15 vol.% of the bulk rock, would be molten at temperatures below ~1100-1150 °C (estimated onset of silicate melting). Thus, the metal phase may have been largely extracted before silicate melting began, permitting efficient extraction of silicate melts [12] and preservation of oxygen isotope heterogeneity [10,11]. If this was the case, what was the nature of ureilite precursor materials? I will discuss possibilities, with implications for the primitive achondrite paradigm.

THE ROLL OF THE DICE: DIFFERENTIATION OUTCOMES AND THE ROLE OF LATE PROTOPLANETARY IMPACTS. W. Daniel Heinze1, 1GRAD, Intl., PO Box 2429, Fredericksburg, Texas, 78624; danheinze@gmail.com.

Introduction: In the terrestrial planets, the abundance of refractory elements appears to decrease smoothly with heliocentric distance, but that of volatile elements is quite variable. Some major contributors to volatile element content in the terrestrial planets are: accretionary contributions (How much was delivered?), mass of the planet (What was the retention potential?), and the presence/persistence of a strong magnetic field (How much of the lighter volatiles were retained for how long?).

Development: Modeling suggests that accretionary contributions of volatiles increase smoothly with heliocentric distance, but the planet size and presence/persistence of a magnetic field are widely varying and depend on small number statistics [1-5]. In particular, recent results suggest that without a highly disruptive planetary-embryo late-accretionary impact, differentiation will result in stratification that is sufficiently strong that it will inhibit the formation of a magnetic dynamo in the core [6]. Late accretion principally occurs by the impact of 10-100 (large) planetary embryos, which have low probabilities of being high-velocity impacts [1,4,5]. Thus it appears that a small number of low probability events have a large impact on the outcome of planetary differentiation and volatile content.

Unique NWA 11119/11558, NWA 7325 (and pairs) and Almahata Sitta individuals MS-MU 011/035: new light on very early parent body differentiation.

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In recent years a set of unique meteorites – achondrites – with partly significantly high contents of plagioclase and/or various silica phases such as cristobalite, trydimit or quartz have been identified. Almahata Sitta individuals MS-MU 011 and later MS-MU 035 were the first meteorites of this new type indicating high-silica trachy-andesitic magmatism, in this case possibly a near-crustal or upper mantle formation on the ureilite parent body. [1,2,6 and refs]

NWA 7325 and pairs represent another unique set of meteorites which was classified as a cumulate olivine-microgabbro containing more than 50% of feldspar – plagioclase and clinopyroxene (diopside). Oxygen isotopy indicates similarities concerning formation and origin to the 2 Almahata Sitta individuals, all plotting in the ureilites region. [1,2]

Last year NWA 11119 (and paired NWA 11558) attracted the meteorite community even further: the silica content of this stone was found to be as high as at least 30%, mainly revealing cristobalite / trydimit and traces of quartz; further main phases are plagioclase – anorthite – and diopside – a fascinating whitish – green rock. Practically all phases are frequently found in small cavities in beautifully crystallized individual crystals. [1-7]

NWA 11575 is the most recent find in this direction, classified as an ungrouped achnodrite, petrologically also a trachy-andesite with an oxygen isotopy in the LL region. [7]

In our projects we have undertaken a series of systematic investigations on several of these meteorites – with the exception of NWA 11575. In our contribution we will mainly focus on

- Mineralogy and phase composition
- Shock degree
- Formation processes
- Magnetic signatures

and summarize our major results [5,6 and refs].

As an example, figure 1 shows the results on magnetic susceptibility which we have obtained these materials.

Figure 1: Magnetic susceptibility: (a) ▲ NWA 11119, (b) ■ NWA 7325 and pairs, (c) ● Almahata Sitta MS MU 011/035. For (a) and (b): the dotted lines indicate the average values, respectively.

MagSus values of NWA 11119 and NWA 7325 and pairs represent the lowest MagSus values which have been measured so far on any meteorites to our best knowledge, please note that both are finds. Therefore, one has to state that these values are not directly comparable with Almahata Sitta MS-MU 011/035 values which is a fall. Also in comparison with terrestrial equivalents, MagSus values are quite low, which means that the concentration of Fe-bearing phases is neglectible. This is confirmed by our mineralogy analyses data: no metals or strongly magnetic Fe-oxides [5].

The preliminary results would support our conclusion that these unique meteorites may probe the crust/upper mantle of a yet unknown planetary body which existed only in a very early period of time of our planetary system.

References:
EARLY EPISODES OF HIGH-PRESSURE CORE FORMATION PRESERVED IN PLUME MANTLE
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Introduction: We report recently published iodine partitioning data between metal and silicate (1). Generation of new iodine partitioning data was motivated by recent geochemical observations demonstrating that plume mantle contains isotopic heterogeneity that originated during the initial differentiation of Earth, in part associated with the short-lived decay of iodine to xenon (2-6). The presence of very early-formed chemical heterogeneity in the modern mantle is surprising because it was thought that Earth's accretion was sufficiently violent to homogenize the entire mantle (e.g., 7).

Early formed isotopic heterogeneity is manifested by tungsten and xenon in primitive components of plume mantle marked by high $^{3}He/\text{He}$ ratios (2-6). It is well-established that tungsten isotope heterogeneity in the solar system is dominantly related to the fractionation of hafnium from tungsten during core formation (e.g., 8). Iodine and plutonium are the short-lived parents to xenon, and our new partitioning measurements demonstrate that the xenon isotopes are also sensitive to core formation because of the siderophile behavior of iodine. It follows that isotopic heterogeneity for tungsten and xenon might reflect incomplete mixing of the mantle following episodes of core formation.

Experimental methods: Experiments were conducted using a laser-heated diamond anvil cell (LDAC) (GSECARS, APS) and a piston cylinder press (Smithsonian) under pressures and temperatures directly relevant to core formation within the deep Earth. A set of lower pressure piston cylinder experiments were also completed to corroborate the LDAC results (Smithsonian). Chemical analyses of the experiments were completed using a field-emission electron microprobe (Carnegie). All LDAC experiments were recovered and prepared for chemical analysis using a focused ion beam (Carnegie).

Short-lived isotopic modeling: We explore the pressure-temperature-timing conditions for core formation that would result in the production of the most extreme tungsten and xenon anomalies reported to date in plume mantle (2-6). We find that these extreme isotopic anomalies are produced within mantle that experienced core formation, on average, earlier and under higher pressure compared to the rest the mantle. Model calculations assume single-stage core formation but the pressure-temperature-timing conditions of core formation are allowed to vary between different parcels of the mantle.

Comparison to other observations: High pressure core formation will also result in the corresponding production of FeO-rich, and correspondingly dense, parcels mantle (e.g., 7) that are predisposed to long-term preservation as chemically distinct reservoirs. This may explain the origin of large low shear velocity provinces (LLSVPs), regions of the mantle associated with plumes that are putatively dense (9,10). Thus, core formation occurring at different times and under different pressures can account for the production and preservation of tungsten and xenon anomalies in plume mantle.

Conclusions: Our hypothesis implies that 1) highly volatile elements, such as iodine, and potentially carbon, hydrogen, sulfur, and nitrogen, were already present within Earth as it experienced core formation – suggesting a minor role for the late veneer in supplying Earth’s volatiles and 2) chemical heterogeneity persisted in the mantle despite the large energies associated with accretion and core formation perhaps physically manifested by LLSVPs.


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SEQUESTRATION OF NITROGEN IN THE CORE DURING ACCRETION C.R.M. Jackson, Z. Du, N.R. Bennett, Y. Fei, E. Cottrell. 1. Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution 2. Geophysical Laboratory, Carnegie Institute for Science

Introduction: Volatile elements (nitrogen, carbon, sulfur, and hydrogen) sustain life, modulate climate, influence mantle dynamics, and alter the physical properties of the core. Correspondingly, the processes that control abundance and distribution of volatile elements within planets fundamentally affect habitability and broad-scale geologic evolution. Volatiles present with bulk silicate Earth (BSE) and chondritic meteorites appear to share a common heritage given their similar isotopic signatures, but the relative abundances of BSE volatiles are elementally fractionated with respect to chondritic precursors (e.g., 1). Among these, nitrogen depletion is most prominent (1-3).

The two major mass-loss processes for volatiles from silicate portion of planets include atmospheric loss and core formation (e.g., 3). Here we investigate how core formation affects the abundance of nitrogen and other volatiles within BSE by performing metal-silicate partitioning experiments. Work to date has predominately been completed under pressure and temperature conditions much less extreme than those associated with core formation within Earth (4-7). Nonetheless, this work demonstrates that nitrogen is siderophile, and therefore lost to the core during accretion, but also that the siderophility of nitrogen is less extreme compared to other volatiles given current partitioning data (e.g. 7). This latter point in the context of the BSE nitrogen depletion suggests that core formation plays a minor role in determining the abundance of volatiles within BSE because core formation is expected to leave BSE relatively enriched in nitrogen relative to the other volatiles. Our focus is on extending the existing nitrogen partitioning dataset to the pressures and temperatures associated with core formation on larger terrestrial bodies – the conditions that appear to dominate core formation within Earth.

Methods: We have conducted nitrogen partitioning experiments in carbon- and sulfur-bearing metal-silicate systems from 1 to 20 GPa and from 1573 to 3500 using a piston cylinder presss (Smithsonian) and laser-heated diamond anvil cell (LH-DAC) (GSECARS, APS). These conditions approach the average pressure and temperature conditions that Earth experienced, as given by single-stage core formation calculations (e.g., 8). Experiments were analyzed using an electron microprobe (Carnegie & Smithsonian). LH-DAC experiments were recovered using a focused ion beam (Carnegie).

Results: Our experimental data indicate that nitrogen partitions preferentially into cores up to the most extreme pressures and temperatures explored here, provided oxygen fugacity remains above ΔIW-4.

Low-pressure data were obtained using a piston cylinder press. These data demonstrate that more reducing conditions, higher temperatures, and higher nickel, carbon, and sulfur concentrations in the metal all make nitrogen less siderophile. Results for the redox and Ni dependencies are consistent with literature partitioning data (4-7), while results for C and S are consistent with the steelmaking literature (9). Interaction parameters for nitrogen with carbon, sulfur, and nickel will be reported. Experiments varying the silicate melt chemistry indicate more polymerized (or higher ionic porosity) silicate liquids favor less siderophile behavior for nitrogen.

Extrapolation of low-pressure data to the temperatures of LH-DAC experiments underpredict the nitrogen partition coefficients measured in these experiments, suggesting a role for pressure in making nitrogen more siderophile. Because of the counteracting effects of temperature and pressure, nitrogen may remain a moderately siderophile element up to the most extreme conditions suggested for core formation within Earth. Core formation under very high pressures may lead to the preferential depletion of nitrogen relative sulfur in bulk silicate Earth given the present work and recent high pressure sulfur partitioning data (10). This raises the possibility that core formation under high pressure was central in shaping the volatile element pattern for BSE.

THE DIFFERENTIATION OF MARS AND ITS SHERGOTTITE SOURCE REGIONS. J.H. Jones\(^1\) and J.I. Simon\(^2\). \(^1\)Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058, USA (jones@lpi.usra.edu). \(^2\)Center for Isotope Cosmochemistry and Geochronology, Astromaterials Research & Exploration Science, EISD-NASA Johnson Space Center, Houston, TX 77058, USA (justin.i.simon@nasa.gov)

**Introduction:** Mars differentiated very early into a core, a depleted reservoir, and an enriched reservoir, where depleted and enriched refer to incompatible lithophile trace elements such as La and U [1, 2]. In particular, isotopic anomalies in \(^{182}\)W from the decay of \(^{182}\)Hf (\(t_{1/2} = 9.2\) Ma) require that this differentiation occurred within 2-3 \(^{182}\)Hf half-lives of the origin of the Solar System (i.e., \(\geq 4540\) Ma [1]). Further, modeling of the combined \(^{146}\)Sm,\(^{142}\)Nd & \(^{147}\)Sm-\(^{143}\)Nd chronometer systems yield a time for the formation of the various shergottite reservoirs of \(4504 \pm 6\) Ma [3]. The Sm-Nd and Hf-W ages may not be comparable, even though they are both rather ancient. For comparison, the oldest ages from a martian rock are Pb-Pb ages from a suite of NWA 7355/7034 zircons, which average \(4436 \pm 25\) Ma [4]. Still, these are \(\sim 100\) Ma younger than the inferred \(^{182}\)Hf-\(^{182}\)W age.

The standard model of [3] for the origin of shergottites and their source regions is essentially: (i) Sili
cate Mars differentiated at \(4500\) Ma as a planet-wide magma ocean crystallized. (ii) Solidification of the magma ocean created a suite of reservoirs which varied from highly depleted to highly enriched. (iii) The timing of this differentiation and the Sm/Nd of the various shergottite reservoirs are constrained by both the \(e^{(142)\text{Nd}}\) and \(e^{(143)\text{Nd}}\) of individual shergottites. (iv) Because the measured \(^{144}\)Sm/\(^{146}\)Nd ratios of individual shergottites are always greater than those required to produce their \(e^{(142)\text{Nd}}\) and \(e^{(143)\text{Nd}}\) signatures, it is interpreted that a loss of a liquid, enriched in Nd over Sm, occurs just prior to the genesis of each and every shergottite. (v) The timing of crystallization for individual shergottites occurred between 150 and 700 Ma. (This scenario does not apply to the two \(\sim 2400\) Ma shergottites, NWA 8159 and NWA 7635 [5, 6].)

**A New Model for Shergottite Petrogenesis:** We offer here an alternative model for shergottite genesis: (i) Bulk Mars differentiated early, while \(^{146}\)Sm was still extant, but the exact time is not known. An acceptable time would be that constrained by the \(^{182}\)Hf-\(^{182}\)W system. A magma ocean may or may not be required. At this time, at least two shergottite Sm/Nd reservoirs were established. These enriched and depleted reservoirs eventually attained \(e^{(142)\text{Nd}}\) signatures of \(\sim 0.45\) and \(\geq 1.0\), respectively. (ii) Later, perhaps as much as 2000 Ma later, a depleted reservoir, having an \(e^{(142)\text{Nd}}\) signature \(\sim 1.0\) and a \(^{147}\)Sm/\(^{144}\)Nd ratio of \(-0.3\), differentiated further and its \(^{147}\)Sm/\(^{144}\)Nd ratio became \(0.60-0.70\). Radiogenic ingrowth until the time of shergottite genesis resulted in this reservoir having an \(e^{(143)\text{Nd}}\) of \(\sim +50\). (iii) Melting of this highly-depleted reservoir in the 700-150 Ma timeframe produced the parent melts of the shergottites. (iv) Interaction with various lithologies on the way to the martian surface modified these parental liquids both chemically and isotopically. In this alternative scenario, missing shergottitic melts, with enriched Nd/Sm ratios, are no longer required. As in the case of the standard model, our alternative does not apply to the 2400 Ma shergottites.

**Discussion:** In our scenario, all whole-rock Sm-Nd isotopic trends are mixing lines, including the 4504 Ma isochron of [3]. Synthetic datasets based on our mixing model produce a linear \(e^{(142)\text{Nd}}\) vs. \(e^{(143)\text{Nd}}\) mixing line having a slope similar to that of actual shergottites and having an \(r^2 > 0.99\). Thus, in terms of Sm-Nd isotopic systematics, the two models presented here cannot be easily distinguished using the present dataset.

Although difficult to distinguish by their respective results, the two models summarized here are physically very different. The standard model has a series of ancient (~4500 Ma) shergottite reservoirs that lose Nd-enriched melts from time to time and then produce shergottitic liquids soon after. It is noteworthy that these putative Nd-enriched products have never been seen in the martian meteorite record. Our model has a younger, prevalent mantle reservoir (PM) lying well off the geochron, which is tapped from time to time to produce shergottitic parent liquids. These liquids then interact with the overlying mantle, lithosphere, and crust to produce the final, erupted shergottite compositions. Local geology may be reflected in the final shergottite composition.

Our model makes some predictions for the shergottite Sm-Nd system, the chief one being that the original 1.3 Ga mixing line of [7] should be regarded as a Sm-Nd bound. This is because this line also passes through our PM composition and the old crustal composition denoted by NWA 7034 [1, 8]. This line was originally invoked on the basis of three shergottites: Shergotty, Zagami, and ALH 77005. In the subsequent 35 years, no new shergottite has plotted to the high-Sm/Nd side of that boundary and we predict that none will.

**Introduction:** Geochemical observations of the eucrite and diogenite meteorites, together with observations made by NASA’s Dawn spacecraft while orbiting asteroid 4 Vesta, suggest that Vesta is the parent of the eucrites and diogenites [1, 2]. Vesta’s likely core is 15% by mass (or 8 volume %) of the asteroid, with a composition of 73.7 weight % Fe, 16.0 weight % S, and 10.3 weight % Ni [3]. The abundances of moderately siderophile elements (Ni, Co, Mo, W, and P) in eucrites require that essentially all of the metallic phase in Vesta segregated to form a core prior to eucrite solidification [4, 5].

**Metal-silicate separation:** For this core composition, iron sulfide begins melting at ~940 °C [6]. However, by the onset of silicate melting at 1100-1150 °C [7], only 40% of the metal phase (or 3-4 volume % of Vesta has melted. Due to the lack of connected melt channels at this low melt fraction [8, 9], metal-silicate separation does not begin until after the onset of silicate melting. Separation of metal from silicates is possible once silicate melting begins, but it is initially quite slow. The likely initial size of melt droplets is set by the size of kamacite and troilite grains in the solid metal, < 45 μm [10]. For such small droplets, the chemical equilibration time between metal drop and silicate is very short [11], so the observed concentrations of moderately siderophile elements in eucrites are easily achieved. However, at appropriate viscosities for the partially molten system, the initial Stokes flow velocities for such small droplets are less than 10^{-6} m/year [12]. Such small Stokes flow velocities are overwhelmed by the turbulent convective velocity in the liquid silicate [13]. As a result, the metal drops initially remain suspended in the magma ocean’s convective flow, effectively forming an emulsion of 20-50 μm metal drops in the liquid silicate.

There will be a spectrum of metal drop sizes; large drops fall faster than small drops, and collisions result in gradual growth of metal drops to larger sizes. Once the metal drops reach ~10 cm in size, their Stokes velocities are comparable to the magma ocean convective velocity, allowing the metal to separate from the silicate. This state is reached once the overall melt fraction exceeds about 50%. At that point, the viscosity is controlled by the silicate liquid rather than by the fraction of solid material and it is appropriate to refer to the molten silicate as a magma ocean. Thus, core formation on Vesta occurs as iron rain sinking through a silicate magma ocean [14].

**Thermal Implications:** The iron rain model for core formation on Vesta requires that silicate melting reaches at least 40-50% partial melt, or 1400-1475 °C. This is at the high end of existing thermal evolution models for Vesta [15, 16] and consequently places strong constraints on the accretion and subsequent thermal evolution of Vesta. These constraints are being explored by linking a parameterization of heat flow in a convecting magma ocean [13] with an existing thermal evolution model for meteorite parent bodies [17]. This model uses finite difference methods to calculate heat transport by thermal conduction with radioactive heating by 26Al and 60Fe in a growing Vesta. Initial results suggest that Vesta may need to accrete within 0.5 million years of the injection of 26Al into the solar nebula in order to achieve the required temperature. A key issue is the role of a high porosity, low thermal conductivity layer at the surface of Vesta. The presence of such an insulating layer plays an important role in the early heating of meteorite parent bodies [18]. On Vesta, this insulating layer was replaced at some point by a high thermal conductivity surface layer of basalt (the eucrites). The timing of eucrite formation with respect to core formation may have been an important control on the core formation process on Vesta.

Primitive chondritic meteorites are the presumed building blocks of the terrestrial planets. As such, any chemical or isotopic differences between chondrites and planetary bodies were likely acquired during planetary accretion and differentiation and can thus provide valuable information on these processes. For instance, the non-chondritic Mg isotope composition of the Earth is attributed to vapor loss during accretionary growth of planetesimals [1]. The possibility of an isotopic signature arising from terrestrial core formation is intensely debated. Evidence from Si and Fe isotopes is inconclusive; the non-chondritic Si isotope composition of the Earth can reflect the presence of isotopically light Si in the core [2] or accretion from volatile-depleted materials [3]. Due to the two common valence states of Fe, isotopic fractionation during silicate differentiation obfuscates any primary, potentially core formation-related signatures.

In order to address this issue, we investigate the Ni isotope composition of the bulk silicate Earth (BSE) and chondritic meteorites. Around 93% of Ni is hosted in the Earth’s core. As such, even modest metal-silicate Ni isotope fractionation, as predicted by experimental work [4], would become apparent as an isotopically light BSE compared to chondrites. Earlier studies disagree whether the BSE Ni isotope composition is chondritic [5] or not [6]. Much of this uncertainty arises from the analytical challenge of resolving the expected small difference in $\delta^{60}\text{Ni}$ ($^{60}\text{Ni}/^{58}\text{Ni}$) of the sample relative to reference material NBS 986 and the choice of samples representative of the BSE. We address these problems through an optimized double spike analytical protocol and careful selection of peridotite sample least affected by secondary processes. For the latter, we have analyzed a suite of samples from the Horoman peridotite massif (Japan) that are exceedingly fresh, free from metasomatic overprint and show no Li or Mg isotope evidence for diffusional disturbance [7]. These peridotites range from relatively fertile (3.5 wt.% $\text{Al}_2\text{O}_3$) to depleted (0.5 wt.% $\text{Al}_2\text{O}_3$) but have homogeneous $\delta^{60}\text{Ni}$ that does not correlate with degree of melt depletion. The average $\delta^{60}\text{Ni}$ of the Horoman peridotites is ca. 90 ppm lower than chondritic meteorites, well outside our analytical reproducibility of <20 ppm. The difference between the BSE and chondrites is of the right sign to be caused by metal-silicate segregation during core formation, but the magnitude of the dichotomy exceeds that predicted in an experimental study [4]. This implies that either there is a significant pres-
Differentiation: Building the Internal Architecture of Planets 2018 (LPI Contrib. No. 2084)

Using the South Pole-Aitken (SPA) Impact Melt Composition to Infer Upper Mantle Mineralogy and Timing of Potential Mantle Overturn. David A. Kring1,3 and Debra H. Needham2,3. 1Center for Lunar Science and Exploration, USRA Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058 (kring@lpi.usra.edu), 2Marshall Space Flight Center (MSFC), 320 Sparkman Drive, Huntsville AL 35805, 3Solar System Exploration Research Virtual Institute.

Introduction: From a few particles of anorthosite in Apollo 11 soil samples, John Wood and others [1-3] quickly deduced the Moon had been surrounded by a lunar magma ocean (LMO) that differentiated, producing an anorthositic crust that forms the ancient crusted highlands of the Moon seen today. The base of the differentiated sequence is expected to have been composed of Mg-rich olivine and olivine with increasing amounts orthopyroxene. The shallowest mantle would then be composed mostly of clinopyroxene and other materials enriched in elements that were incompatible during LMO crystallization. That sequence has an inverted density profile that may have prompted an overturn of the cumulative pile to stabilize the density structure of the lunar interior (e.g., [4-7]). Ilmenite-rich material, carried downward by the overturn, became an important source region for pyroclastic basalts like those at Apollo 17.

A Probe of the Mantle: Impact bombardment altered the crust, in some cases melting the anorthosite, any intrusions within it, and, in the largest impacts, the upper mantle. A simple calculation [8] indicates ~10^8 km^3 of impact melt was produced. Approximately half (if not more) of the impact melt volume was produced by the SPA basin-forming event. The largest fraction of the melt stayed within the central melt pool. That melt may have differentiated, producing a new series of layered lithologies. In the case of SPA, liquid lines of descent suggest olivine may have crystallized and settled downward. Progressive crystal fractionation would have driven the remaining liquid towards noritic compositions [9-11], which is observed today.

A more sophisticated examination of SPA impact melt differentiation [12], based, in part, on a hydrocode assessment of the SPA impact event and depth of melting [13], also produced noritic material, but only if the mantle had not yet overTurned. Alternatively, the results suggest any mantle overturn was not a global event.

Implications for Timing: The duration of the LMO ranges from 10 Myr based on heat loss rates through a simple conducting lid [7], to ~100 Myr based on tungsten ratios measured in low- and high-Ti mare basalts and KREEP [14], and ~200 Myr based on heat loss rates through a tidally deforming lid [15,7]. Cumulate overturn is hypothesized to have occurred toward the final stages of LMO solidification, after the cumulative density inversion developed [4,5,7,16]. That implies the SPA-forming impact occurred significantly earlier than currently thought if, for example, the LMO had a simple conducting lid, at ~4.5 Ga [7], or the LMO solidification and cumulative overturn were delayed to ~4.3 Ga, a delay accommodated by tidal heating of the conducting lid [15,7]. The latter is consistent with a recent model of the impact flux to the Moon, which was used to estimate an age of ~4.35 Ga for the formation of SPA [17] and consistent with a crater-counting surface age of ~4.26 Ga [18]. If SPA did indeed form prior to the hypothesized LMO cumulative overturn, it is possible that the impact event triggered the overturn process, affecting a broad portion, if not all, of the lunar interior structure, though further analyses are required to verify this hypothesis.

Conclusions: The upper mantle of the Moon at the time of the SPA impact featured clinopyroxene rather than olivine. If mantle overturn occurred, it may have been triggered by the SPA impact event on the lunar farside. That impact event has also been implicated in the origin of a magmatic epoch on the nearside [19].

METEORITE DICHOTOMY IMPLIES THAT JUPITER FORMED EARLY T.S. Kruijer¹, C. Burkhardt¹, G. Budde, T. Kleine ¹, ¹University of Münster, Institut für Planetologie, Münster, Germany. ²Lawrence Livermore National Laboratory, Nuclear and Chemical Sciences Division, Livermore, CA, USA (thomaskruijer@gmail.com)

Introduction: The formation of Jupiter had a substantial effect on the dynamics of the solar accretion disk [1]. Thus, knowing the age of Jupiter is key for understanding the evolution and structure of the Solar System. Here we demonstrate that Jupiter’s formation time can be derived using the isotopic signatures of meteorites. Nucleosynthetic isotope anomalies reveal a fundamental genetic dichotomy between ‘carbonaceous’ (CC) and ‘non-carbonaceous’ (NC) meteorites [2,3]. This distinction either reflects a temporal change in disk composition or the spatial separation of materials accreted inside (NC) and outside (CC) the orbit of Jupiter [1-3]. If the latter is correct, then the age of Jupiter can be determined by assessing the formation time and longevity of the NC and CC reservoirs. In a recent study [4] we tested this case using the W and Mo isotopic signatures of iron meteorites. These samples are fragments of the metallic cores from some of the oldest planetesimals, making them ideal samples to search for the effects of giant planet formation on the dynamics of the solar disk. To this end, we investigated ~70 iron meteorite samples, used nucleosynthetic Mo isotope signatures to link them to either the NC or CC reservoirs, and determined the timing of core formation in their parent bodies using the HF–W system ($t_{1/2} \sim 9$ Ma).

Mo and W systematics: In a plot of $^{94}$Mo vs. $^{96}$Mo (0.01% deviations from terrestrial standard values), the iron meteorites define two distinct $s$-process mixing lines (Fig. 1), demonstrating that some iron meteorite groups stem from the NC reservoir, but others from the CC reservoir. A similar genetic dichotomy is seen for W, where NC irons have lower $^{182}$W from $\sim$3.4 to $\sim$3.3, and no $^{183}$W anomaly, whereas the CC irons have higher $^{182}$W of ca. $\sim$3.2 and nucleosynthetic $^{183}$W excesses (from ca. $+0.1$ to $+0.5$).

Fig. 1: Iron meteorites (closed symbols) and chondrites (open symbols) show two distinct trends, separating a CC (blue) from a NC reservoir (red).

Fig. 2: Stages of Jupiter’s growth history.

Implications: The higher $^{182}$W of CC irons indicate a later time of core formation compared to NC irons, which in turn might reflect different accretion times of $<0.4$ Ma (NC irons) and $\sim$1 Ma (CC irons). Accretion of CC irons at $\sim$1 Ma after CAIs implies that by this time the NC and CC reservoirs had already separated (Fig. 2). As both reservoirs contain chondrites, which accreted at $\sim$2 Ma in the NC reservoir (ordinary chondrites) and until $\sim$3–4 Ma in the CC reservoir (carbonaceous chondrites) [5], and because there is no evidence for mixing between the NC and CC reservoirs, both reservoirs remained isolated from each other until parent body accretion terminated at $>3$–4 Ma after CAIs.

The only plausible mechanism that can efficiently separate the NC and CC reservoirs for an extended period of time is the formation of Jupiter [1,6]. The growth of Jupiter beyond >20 Earth masses (ME) inhibited the inward drift of small particles [6], implying that by the time the CC reservoir formed (i.e., $\sim$1 Ma after CAIs), Jupiter already had a size of $>20$ ME. Once Jupiter reached a mass of 50 ME, a gap opened in the disk, which was followed by scattering of bodies from beyond Jupiter’s orbit (i.e., CC bodies) into the inner solar system [7]. This scattering of CC bodies cannot have started before $\sim$3–4 Ma, because CC bodies continued to form until at least that time. Thus, Jupiter reached $\sim$50 ME later than $\sim$3–4 Ma after CAIs.

EFFECT OF IMPACTS ON THE COOLING RATES OF DIFFERENTIATED PLANETESIMALS.

**Introduction:** Iron meteorites come from the cores of differentiated planetesimals. The cooling rates they record provide valuable insight into the thermal evolution and structures of their parent bodies. Haack et al. [1] simulated the thermal evolution of differentiated bodies and found that a core would cool uniformly, and the cooling rate was a function of the planetesimal size. The Haack et al. [1] model, however, did not allow for collisions as the body cooled. During the first 100 Myr of Solar System evolution, planetesimals would have experienced frequent and energetic collisions [2].

Ciesla et al. [3] found that a collision of a small impactor (<10% radius of target) into a radiogenically heated chondritic, ~100 km radius planetesimal could uplift material at depth, bringing it closer to surface, and allow it to cool more quickly than expected. Similarly, it has been shown that large-scale hit-and-run collisions of embryos could strip some bodies of their mantles, leaving exposed metallic bodies that then cool rapidly producing the non-uniform cooling rates found in iron meteorite groups such as the IVA’s [4,5]. As both types of collisions are likely, here we report on our findings of the effects small impacts have on differentiated, 100 km planetesimals, the types of bodies from which many main group irons are expected to originate [1,4].

**Model and Results:** We model the thermal evolution of a planetesimal from accretion through differentiation and subsequent cooling, largely following the methodology and parameters from [7]. These planetesimals are then impacted at three different times in their histories; when the entire body is molten, when the mantle is mostly crystallized and the core is still partially molten, and when the whole body has cooled to near ambient temperatures.

Sub-catastrophic collisions into planetesimals near their peak temperatures (when the entire body is largely molten), have little effect on the core as the post-impact body returns to a state where the core is covered by the insulating mantle. Impacts into cold, completely solid bodies also have little effect as the impacts do not affect the temperature in the core. However, impacts that occur when the planetesimal’s mantle is mostly solidified, but the core still retains melt, can have their cooling rates significantly affected. Figure 1 shows the final structure of a 100 km-radius impacted body (10 km impactor at 6 km/s). The exposed core loses heat much faster than if the impact never occurred. The histogram shows that the cooling rate may increase by over an order of magnitude beyond what would otherwise be predicted (red line). Similar results have been observed in 50 and 200 km-radius planetesimals. We are currently quantifying these effects and how they can be used to infer properties and histories of their parent bodies.

HEAT PIPE PLANETS. William B. Moore1,2, Justin I. Simon1, 1Department of Atmospheric and Planetary Sciences, Hampton University, Hampton, Virginia 23668, USA (bill.moore@nianet.org). 2National Institute of Aerospace, Hampton, Virginia 23666, USA. 3Center for Isotope Cosmochemistry and Geochronology, ARES, NASA-JSC, Houston, TX 77058, USA (Justin.I.Simon@NASA.gov).

Introduction: Exploration of terrestrial bodies in our Solar System has largely emphasized the different geologic histories experienced by the different bodies: Mercury’s early contraction, Venus’s desiccated, relatively young surface, Earth’s plate tectonics, the Moon’s bimodal crustal composition and non-equilibrium shape, Mars’ hemispheric dichotomy and isolated volcanic edifices, Io’s exceptionally rapid volcanic resurfacing. In the face of such diversity and the likely discovery of still different planetary surfaces in exoplanetary solar systems, it is necessary to explore what aspects of geological history may be held in common by all of these terrestrial bodies, in order to address the larger question of what features may be shared by terrestrial planets across the galaxy.

Despite their differences the surfaces of all terrestrial bodies other than Earth reveal remarkable but as yet unexplained similarities: endogenic resurfacing is dominated by plains-forming volcanism with few identifiable centers, magma compositions are highly magnesian (mafic to ultra-mafic), tectonic structures are dominantly contractional, and ancient topographic and gravity anomalies are preserved to the present. We have proposed that cooling via volcanic heat pipes [e.g., 1,2] may explain these observations and provide a universal model of the way terrestrial bodies transition from a magma-ocean state into subsequent single-plate, stagnant-lid convection or plate tectonic phases. We have shown that the end of the magma ocean is not the point at which the Solar System’s rocky bodies diverge in their evolution. Specially, we review the records of the Solar System’s stagnant-lid terrestrial bodies to test whether they too may have experienced an early phase of heat-pipe cooling as observed at present on Io.

Conceptual Model: A planet that is cooling via heat-pipes experiences persistent global volcanism that constantly resurfaces the planet. Older layers are progressively buried and advected downwards to form a thick, cold, single-plate lithosphere. Because each layer is deposited at the surface and then pushed down into smaller and smaller spherical areas, lithospheric contraction is a global and persistent process. At the base of the lithosphere, material is reabsorbed into the mantle or remelted, feeding continuing volcanism. Heat-pipe operation leads to: 1) Cold, thick and strong lithospheres, 2) Dominance of compressive stresses, 3) Continuous replacement of lithospheric material, 4) High melt-fraction (mafic to ultra-mafic) eruptions, and 5) A rapid transition to conductive lid or plate tectonic behavior (Fig. 1). Solar System-wide preservation of ancient, large-scale topography and density variations, predominance of mafic volcanic material, absence of significant extensional strain, and broad regions of uniform surface ages indicating a rapid decline in resurfacing are common features of the terrestrial planets that support early heat-pipe cooling.

![Figure 1. Illustration of terrestrial planet heat flow vs. internal temperature. The sense of evolution as heat sources and internal heat content decline is shown by arrows. The known terrestrial bodies are labeled, LTP stands for Large Terrestrial Planet, and the initial magma ocean stage is indicated. Heat loss is high and thermal evolution is rapid in the upper right of the diagram, where the magma ocean gives way to heat pipes, and heat flow decreases as heat pipes transition to either plate tectonics or rigid lid convection.](https://example.com/figure1.png)

Summary: The geological and geochemical evidence from the terrestrial planets in our Solar System is consistent with heat-pipe operation providing the main source of crustal formation and endogenic resurfacing. Since the equilibrium heat flux of a planet scales as mass/area (for radiogenic heating), terrestrial planets more massive than the Earth should experience longer heat-pipe episodes prior to the initiation of plate tectonics. Due to compressibility of terrestrial materials, a planet twice as massive as Earth should take more than twice as long to cool. For massive terrestrial planets up to 5 Earth masses, the lifetime of the heat-pipe phase may exceed the lifetime of their parent stars and thus any subsequent plate-tectonic phase may never be observed, while smaller bodies such as Mars never achieve sufficient stress to start plate tectonics [3].

**Introduction:** Mars is the only major planet in our solar system besides Venus that does not currently host a global magnetic field generated by an internal dynamo [1]. Crustal remanent magnetism indicates that a magnetic dynamo existed after accretion but ceased before the formation of the Argyre and Hellas impact basins at 4 to 4.1 Ga [2]. Remanent magnetization in the Martian meteorite ALH84001 also evidences a dynamo around 4 Ga and perhaps beginning immediately after formation of the core [3]. Standard models for its demise rely on the cooling rate of the core quickly dropping below the critical amount required to sustain vigorous convection [e.g., 4]. Thermal convection will only occur if the total heat flow exceeds that conducted along an adiabatic temperature gradient (i.e., $Q_c > Q_{ad}$). However, chemical processes in the core also strongly affect the prospects for dynamo activity. Here we demonstrate that progressive hydrogenation of the core may impede a dynamo throughout geologic time even if elevated core/mantle heat flow persists beyond the Noachian.

**Transporting hydrogen into the core:** The partition coefficient for hydrogen between ringwoodite and iron at pressures appropriate to the core/mantle boundary of Mars was measured as ~26, which implies that ~97% of hydrogen should partition into the metallic phase at thermodynamic equilibrium [5]. We parameterize the mass flux of hydrogen across the core/mantle boundary as $M_{H,1} = A_c C_w f_H \rho_m n_H v_m$, where $A_c$ is the surface area of the core, $C_w$ is the mass fraction of water in the basal mantle (~0.02 for saturated ringwoodite), $f_H$ is the mass fraction of hydrogen in water, and $\rho_m$ is the density of the lower mantle. We assume that the overturn velocity of the basal mantle equals a constant (~5 cm/s) times the average convective velocity in the mantle ($v_m$). Partitioning rates would decrease by ~4 orders-of-magnitude without convective rejuvenation given the slow diffusivity of hydrogen in ringwoodite.

**Downward entrainment of hydrogen:** Hydrogenation represents a sink of gravitational energy that counteracts secular cooling and/or radiogenic heating, which would otherwise drive convection. We derive the maximum mass flux compatible with a dynamo using a one-dimensional, parameterized model adapted from studies of Earth’s core [6,7]. Double-diffusive convection in the layered regime transports hydrogen downwards into the initially well-mixed region more efficiently than pure diffusion [8]. We calculate the downward entrainment rate into the convecting region as $M_{H,2} = \rho_c (D_H / k_c) (\alpha_r / \alpha_h) (Q_c - Q_{ad}) R_p N u_H$, where $R_p \sim 5$ is the density ratio allowing double-diffusive instability, $D_H$ is the diffusivity of hydrogen in the core, $k_c$ is thermal conductivity, and $\alpha_r$ and $\alpha_h$ are the coefficients of thermal and compositional expansion, respectively. The chemical Nusselt number ($N_u$) is roughly the thickness of each convecting layer divided by the width of the diffusive interfaces. We generate thermochemical histories for Mars built on a simple, parameterized model [9]. Without fine-tuning, we find that the core/mantle heat flow would remain super-adiabatic for ~3 Gyr. However, hydrogenation will suppress convection in the core and thus a dynamo as long as the individual layers in the double-diffusive zone are >1 m thick ($N_u > 15$) and ringwoodite in the lower mantle contains >0.5 wt% water. Roughly equal masses of water are lost via degassing to the surface and redox reaction with the core.

**Importance of initial mantle stratification:** Some compositional heterogeneity in the lower mantle is required to delay hydrogenation of the core. Hydrogenation must occur at a slow rate for ~500 Myr to form a double-diffusive zone that begins at the core/mantle boundary. Otherwise, steep compositional gradients would create a purely diffusive layer that effectively sets $N_u = 1$ and prevents enough entrainment. The NASA InSight mission is expected to determine the exact radius of the core. If the radius is within a certain range, then the lower mantle may have started within the stability field of bridgmanite, which has a much lower water storage capacity than ringwoodite. Hydrous ringwoodite would form at the core/mantle boundary only after some cooling because of the negative Clapeyron slope of the post-spinel transition. Solidification and subsequent overturn of a magma ocean could alternatively create a compositional density gradient that delays convective rejuvenation of the lower mantle [10]. Ultimately, constraining the compositional configuration of the mantle after differentiation is essential to understanding the history of magnetism on Mars.

DIFFERENTIATION: BUILDING THE INTERNAL ARCHITECTURE OF PLANETS 2018 (LPI Contrib. No. 2084)

FELDSPATIC ROCK IN ANCIENT CRUST, N. HELLAS, MARS: IMPLICATIONS FOR EARLY MANTLE CONDITIONS. M.S. Phillips1, J. E. Moersch1, and C. E. Viviano2, 1Earth and Planetary Science Department, University of Tennessee, Knoxville, TN 37996-1526 (mphill58@vols.utk.edu), 2Johns Hopkins University Applied Physics Lab, Laurel, MD 20723.

Introduction: The earliest stable crusts of rocky bodies likely formed via differentiation from magma oceans [1]. The oldest crustal materials on Mars may represent such magma-ocean-derived crust [2], and characterizing these outcrops can help constrain early mantle conditions. In this study, we used Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) mapping data to characterize the primary igneous mineralogy associated with ancient crustal outcrops exposed in uplifted massifs north of Hellas basin.

Geologic Background: Hellas basin (~42° S, 70° E) is the largest unambiguous impact structure on Mars (D ~ 2300 km). The ~4 Ga impact exhumed deep crustal materials and likely the upper mantle [3, 4]. Crustal thinning and extension caused structural uplift circumferential to the basin exposing deeply buried material in mountainous blocks called “uplifted massifs” [5]. These massifs provide a window into the deepest crust (and potentially upper mantle, e.g., [3]) of Mars, and are useful for constraining Mars’ early mantle composition.

Data and Methods: To analyze the km-scale extent of uplifted massifs and broad absorption features of igneous silicate minerals in the VSWIR, we employed CRISM 200 m/pixel multispectral mapping data. Mineral identifications were made using add-on tools for the Environment for Visualizing Images (ENVI) software, and mapping was done using ArcGis.

Results: We identified 188 outcrops with plagioclase, olivine, or pyroxene spectra in northern Hellas massifs (Fig. 1A). Low-calcium pyroxene (LCP), olivine, and plagioclase were the most common minerals identified with one identification of high-calcium pyroxene (HCP). The compositions appear correlated with elevation on the Hellas rim (Fig. 1). Plagioclase and olivine occur at lower elevations than pyroxene.

Discussion: The ostensibly stratified distribution of minerals along the northern Hellas rim may be indicative of an original stratigraphy. If the mechanism of exhumation was structural uplift rather than impact ejecta, we would expect any exposed stratigraphy to be representative of the original layering and not inverted. Uplifted massifs also display an unexpected preponderance of plagioclase. Although plagioclase is the most common mineral on the Martian surface, its detection in the VSWIR is rare [see, e.g., 6]. Several identifications of plagioclase have recently been made with CRISM in study areas adjacent to [7, 8] and overlapping with [9] this study. Our results expand upon previous detections of feldspathic outcrops, more than doubling the number of these detections. Interpretations of feldspathic outcrops have included felsic, anorthositic, and plagioclase-phryic basaltic [7, 9, 8 respectively]. Magma ocean scenarios potentially consistent with the production of a feldspathic component to the early crust are: 1) a deeply-sourced melt produced by cumulative overturn of a whole mantle magma ocean, or 2) a shallow magma ocean [e.g., 10]. We plan to expand our survey to uplifted massifs around Argyre and Isidis basins, to analyze the spatial distribution of identified mineralogy, and to further analyze the nature of feldspathic outcrops. The spatial distribution of ancient crustal minerals may help constrain the spherical harmonic degree of mantle overturn and subsequent crustal production [e.g., 10].

Geochemical Constraints on the Size of the Moon-Forming Giant Impact

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Recent models involving the Moon-forming giant impact hypothesis have managed to reproduce the striking isotopic similarity between the two bodies, albeit using two extreme models: one involves a high-energy small impactor that makes the Moon out of Earth’s proto-mantle; the other supposes a gigantic collision between two half-Earths creating the Earth-Moon system from both bodies. Here we modeled the geochemical influence of the giant impact on Earth’s mantle and found that impactors larger than 15% of Earth mass result in mantles always violating the present-day concentrations of four refractory moderately siderophile trace elements (Ni, Co, Cr, and V). In the aftermath of the impact, our models cannot further discriminate between a fully and a partially molten bulk silicate Earth. Then, the preservation of primordial geochemical reservoirs predating the Moon remains the sole argument against a fully molten mantle after the Moon-forming impact.
THE COMPOSITION AND MINERALOGY OF EXOPLANETS, USING THE HYPATIA CATALOGUE: IMPLICATIONS FOR EXTRASOLAR PLATE TECTONICS AND MANTLE CONVECTION. K. D.
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**Introduction:** Astrophysical studies reveal that many nearby stars have orbiting planetary bodies (exoplanets), prompting well-founded curiosity as to exoplanet compositions and their tectonic status. We present a new analysis of ca. 900 stars in the Hypatia Catalogue [1], to complement recent estimates on exoplanet mineralogy [1, 2]. Like these ongoing studies, we assume that exoplanets have compositions identical to the stars they orbit. We choose a subset of the Hypatia Catalogue where each of Si, Al, Fe, Mg, Ca, Na, and K are reported. Mantle mineralogy is then estimated for Earth-sized exoplanets (for straightforward comparison), assuming that core formation is equally efficient as on Earth. The latter assumption is implemented as two cases: assume 1) identical partitioning of Fe between silicate mantle and bulk planet, or 2) that core formation yields Bulk Silicate Mantles (BSMs) with 8 wt. % FeO, as on Earth, with all remaining Fe going to form the core. We then apply the algebraic methods of Thompson [4] to transform residual BSMs into mineral proportions, using mineral compositions from [5], chosen so as to reproduce terrestrial mantle mineral proportions in [6, 7], when terrestrial BSMs [e.g., in 5, 8] are used as input.

As with [2] we find that Earth is Fe-rich and that most exoplanets will have slightly smaller metallic cores; our two Fe-partitioning models yield similar results, with exoplanet core radii of +5% to -21% relative to Earth. When accounting for changes in gravity, these translate to Upper Mantle/Lower Mantle boundaries that range from -32 to +64% relative to Earth’s 660 km boundary, varying negatively with core radius.

But our findings diverge from [2] in important ways. For example, we find that quartz saturation in exoplanet mantles may be rare; perhaps only 1-2% of exoplanets are sufficiently SiO$_2$-rich. Rather, most exoplanets have peridotite or pyroxenite mantle mineralogies (Fig. 1), and SiO$_2$-rich exoplanets (BSMs having >50% SiO$_2$, which are 20% of our database) may have upper mantles that consist largely of orthopyroxene (Opx), converting to majorite garnet in their transition zones.

These pyroxenite planets might also exhibit uniquely limited tectonic activity. Experimental studies suggest that Opx-rich BSMs may have higher viscosities (by a factor of 10$^7$ [9]), and lithospheres (or “lids”) with higher yield strengths (esp. at <700°C [10]) compared to olivine (Ol)-dominated systems; both these qualities may inhibit mobile lid (plate tectonic) behavior (e.g., [11]).

Yet another obstacle to tectonics on SiO$_2$-rich planets, or at least a barrier to whole mantle convection, is the increased stability of majorite-rich garnet in their transition zones. Pyroxenites and peridotites both yield basaltic partial melts that are effectively the same with respect to major oxides. Thus, basaltic crusts, and by implication, potential subducted slabs, should have density profiles similar to eclogite (e.g., [12]), regardless of BSM composition. But upon subduction, these slabs will meet very different mineralogical environments, and slabs may be positively buoyant in SiO$_2$-rich planets at pressures > 14 GPa, as majorite garnet becomes a dominant transition zone phase. By contrast, SiO$_2$-poor BSMs are likely to be periclase-saturated throughout their upper mantles, and may feature enhanced subduction and convection.

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**References:**
DIVERGENT EVOLUTIONARY PATHS OF VESTA AND CERES. C. A. Raymond, J. C. Castillo-Rogez, H. Y. McSween, C. T. Russell, and the Dawn Science Team. 1Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, carol.a.raymond@jpl.nasa.gov, 2University of Tennessee, Knoxville, TN, 3IGPP/ESS, University of California, Los Angeles, 595 Charles Young Drive E., Los Angeles, CA.

Introduction: The Dawn mission explored two massive protoplanets in the main asteroid belt, Vesta and Ceres, that are fossils from the earliest epoch of our solar system’s formation. Dawn’s data have provided evidence that these bodies formed very early, within the first few m.y. after CAIs, yet they followed divergent evolutionary paths. Prior to the Nice [1] and Grand Tack [2] models, Ceres and Vesta were thought to have formed in the same part of the protoplanetary disk near their current locations [3], with their differences ascribed to a delay in the formation of Ceres with respect to Vesta. The Dawn mission’s exploration of Vesta and Ceres [4] has advanced our knowledge of their internal evolution and surface geology and composition, which elucidates their early histories and adds constraints on early solar system processes. These bodies offer remarkable examples where differentiation state can help constrain accretional environments.

Dawn’s Results: Dawn’s data confirmed Vesta as the parent body of the HED clan, and by inference that Vesta melted, forming at least a partial magma ocean, and a large iron core. Geochemical and thermal evolution modeling informed by HED compositions and Dawn’s gravity and shape data indicate Vesta formed <1.5 m.y. after CAIs of volatile-depleted chondritic materials [5, 6]. However, in contrast to the pre-Dawn paradigm, gravity and spectral data support a complex magmatics evolution, resulting in a compositionally stratified mantle, with olivine sequestered in the deep mantle and eruption of evolved melts. Such complexity can explain the apparent distinct magmatic reservoirs implied by trace elements in the HED clan. Dawn’s data revealed that differentiation on a small planet appears to be more complex than envisioned by study of meteorites.

Ceres, the only dwarf planet in the inner solar system, was known to be water-rich before Dawn arrived. However, contrary to the expected ice-rich, viscously-relaxed smooth surface resulting from physical (ice/rock) differentiation and freezing of an ancient subsurface ocean, its surface has many craters, implying a mechanically strong thick crust [7]. However, the lack of large craters and Ceres’ gravitationally-relaxed shape implies that the strong crust overlies a weaker deep interior [8, 9]. The globally homogeneous distribution of minerals across the surface [10, 11] and the distribution of [H] and [Fe] relative to chondrites [12] indicates that Ceres’ interior experienced pervasive alteration. Local morphology and the enigmatic faculae indicate recently active processes on Ceres driven by brine cryovolcanism [13, 14]. These data attest to a complex evolution driven by extensive water-rock interaction, resulting in partial differentiation, redistribution of heat-producing elements, and formation of a global ocean [15]. The presence of liquid brines at depth even to the present day is indicated by the global shape [9] and recent cryovolcanism.

Implications for Early Solar System Processes: It has been suggested that Vesta and Ceres accreted from similar chondritic feedstocks but at different times, i.e., with different short-lived radioisotope budgets [4, 17]. The abundance of Al-26 in earlier accreting Vesta would lead to rapid loss of volatiles, while Ceres could have preserved the bulk of its volatiles. However, the remarkable discovery of ammoniated clays on Ceres’ surface [10] suggests very different starting compositions for Vesta and Ceres, and especially a much greater ice fraction for the latter. Vesta’s hot, dry evolution and Ceres’ much milder thermal history can be primarily attributed to the abundance of water in Ceres that helped moderate internal temperature via latent heat and hydrothermal circulation [17, 18].


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Introduction: Decay of $^{107}$Pd to $^{107}$Ag has a half-life of 6.5x10$^6$ Ma [1]. Because these elements are siderophile but also volatile, they offer potential constraints on the timing of core formation as well as volatile addition [2]. Initial modelling has shown that the Ag isotopic composition of the bulk silicate Earth (BSE) can be explained if accretion occurs with late volatile addition [2]. These arguments were tested for sensitivity for pre-cursor Pd/Ag contents, and for a fixed Pd/Ag ratio of the BSE of 0.1. New Ag and Pd partitioning data [3-7] has allowed a better understanding of the partitioning behavior of Pd and Ag during core formation. The effects of S, C and Si, and the effect of high temperature and pressure have been evaluated. We can now calculate D(Ag) and D(Pd) over the wide range of PT conditions and variable metallic liquid compositions that are known during accretion. We then use this new partitioning information to revisit the Ag isotopic composition of the BSE during accretion.

Partitioning: Metal/silicate partitioning can be predicted for siderophile elements using the expression which has been derived elsewhere [8]:

$$\ln D(i) = a_i \ln f_O + b_i + c_i T + d_i P + e_i$$

where $a_i$ is the activity of element i in Fe metallic liquid, $b_i$ is the ratio of non-bridging oxygens to tetrahedrally coordinated cations and is a gauge of silicate melt compositional variation, and the coefficients $a_i$, $b_i$, $c_i$, $d_i$, and $e_i$ are derived by multiple linear regression of various datasets. $a_i$ for Ag and Pd are calculated using an activity model based on interaction parameters with c, g, and h are derived from multiple linear regression of various datasets. $a_i$ for Ag and Pd are calculated using an activity model based on interaction parameters [9,10]. Pd partitioning data compiled by [8] was combined with the activity model to derive new regression coefficients for Pd [9]. Ag partitioning data [3-6, 11,12] have been combined with Ag activities [10] to derive new regression coefficients for Ag [10]. Both Pd and Ag partition less into FeSi alloys than pure Fe, while Ag is more and Pd less siderophile in FeS alloys. Both elements have low valence in silicate melts and thus are only weakly dependent on $f_O$ and silicate melt composition. With increasing temperature and pressure, D(Ag) and D(Pd) become less siderophile. All these effects are captured with the regression coefficients that can be used to model the Pd and Ag content of an evolving magma ocean.

Model calculations and results: The $^{107}$Ag/$^{108}$Ag isotope composition of the mantle is calculated using pre-cursor Pd/Ag = 2.81. 5.6, and 11.2. $^{107}$Pd/$^{108}$Pd$^\infty$ = 5.9x10$^{-5}$ and $\lambda$ = 1.06638x10$^{-7}$ [2]. The $^{107}$Ag/$^{108}$Ag ratio is usually normalized to the value of a standard using the epsilon notation where $\epsilon^{107}$Ag = $\left(\frac{^{107}}{^{107}}\right)_{\text{sample}} / \left(\frac{^{107}}{^{107}}\right)_{\text{standard}} - 1 \times 10,000$. Using our partitioning expressions and a simple model of continuous core formation and core-mantle equilibration, we calculate the $\epsilon^{107}$Ag in the mantle during Earth accretion. The Pd/Ag ratio of the mantle changes from 0.001 to ~ 100 during accretion. The low Pd/Ag ratio during early accretion reflects high D(Pd) and relatively low D(Ag) metal/silicate. As accretion proceeds and PT conditions of metal-silicate equilibrium increase (and core Si content increases), D(Pd) decreases, while D(Ag) increases, thus causing an overall increase in mantle Pd/Ag. If the Earth grows in a 70 Ma timeframe, the model yields a peak of $\epsilon^{107}$Ag ~ 8 near 18 Ma, which decays down to values near $\epsilon^{107}$Ag = -1.4 by 70 Ma (Pd/Ag=5.6). Because the $\epsilon^{107}$Ag of BSE is -2.2 ± 0.7 [2] and Earth likely accreted on a time frame of 70 to 100 Ma, these calculations show that with the variable Pd/Ag ratios, the BSE Ag isotopic composition can be almost achieved with core formation and the presence of Ag during accretion. Later accretion of low $\epsilon^{107}$Ag chondritic material would further decrease the $\epsilon^{107}$Ag values within BSE range [2].

An aspect of our modelling may justify further exploration. The BSE $\epsilon^{107}$Ag value intermittently becomes high during accretion with the variable Pd/Ag ratios. This peak occurs early for Earth and has time to decrease by the end of accretion through extensive Ag sequestration into the core. For Mars, however, the timescale of accretion and differentiation is much shorter than for Earth [13,14], and martian meteorites may thus have preserved this high Ag signal, which is distinct from BSE by more than +0.5 $\epsilon^{107}$Ag.

Ferric iron production in magma oceans and evolution of mantle oxidation state. Laura K. Schaefer¹,², Lindy T. Elkins-Tanton², Kaveh Pahlevan², ¹lschaefer@asu.edu, ²Arizona State University, School of Earth and Space Sciences, Tempe, AZ.

Introduction: Magma oceans are ubiquitous in the early Solar System, and likely in planet-forming regions around other stars as well [1]. Core formation likely occurs simultaneously with magma ocean formation. Models typically assume no ferric iron within the mantle during core formation. However, recent experimental work [2,3] shows that ferric iron production may increase at high pressures, suggesting that ferric iron in the early magma ocean may be non-negligible in determining the oxygen fugacity of the system. The oxygen fugacity of the magma ocean will affect trace element partitioning between the mantle and core [4], as well as the composition of the outgassed atmosphere [5,6].

Oxidizing the magma ocean: Wade & Wood [4] suggest that the mantle self-oxidizes due to disproportionation of Fe²⁺ to Fe³⁺ and metallic Fe in the lower mantle. Rubie et al. [7] finds that the oxygen fugacity of material accreted to the Earth must have been initially reduced and become progressively more oxidized in order to explain the trace element abundances. However, the final oxygen fugacities of these models is generally still too low to explain the Earth's present day value. For instance, the model of [4] uses an increase in fO₂ from IW - 4 to IW - 2, whereas the highest fO₂ in [7] is IW - 1.9.

Model Description: The model includes metal/silicate equilibration at the base of the magma ocean, using the partitioning model of [7] to determine the major element abundances in the core and mantle. We include the disproportionation reaction 3Fe²⁺ → 2Fe³⁺ + Fe⁰ occurring in the silicate melt phase (rather than due to crystallization of perovskite) to produce the initial Fe³⁺ abundance, using data from [2,3] for the silicate melt oxides.

After metal/silicate equilibration, we adapt the magma ocean crystallization model of [8,9] to include Fe²⁺ and Fe³⁺ incorporation into mantle minerals. The model calculates the composition of progressive solid layers using a partitioning model as solidification proceeds from the base of the mantle upwards. The abundance of Fe³⁺ in the melt is set by equilibrium with the crystals forming at the base of the magma ocean.

Results: Initial production of ferric iron depends on the equilibration pressure of core and mantle materials. As pressure increases, ferric iron content increases as well. Exact abundances of ferric iron produced depend on the fit to the thermodynamic data for the silicate melt oxides.

Partitioning results indicate that the magma ocean progressively oxidizes as it crystallizes from the bottom up. Elkins-Tanton [8] showed that the crystallizing phases become progressively enriched in FeO at the top of the mantle. We find that Fe³⁺ follows the increase of FeO with crystallization.

Conclusions: We find that self-oxidation of the magma ocean to present day oxidation state near QFM can occur during the magma ocean phase due to high pressure production of ferric iron. Partitioning results suggest that the early upper mantle could have been more oxidized than present day prior to mantle overturn. This has implications for the evolving composition of the earliest atmosphere.


Using stable isotopes to probe planetary differentiation and evolution.

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Introduction: The differentiation of planetesimals occurred at high temperature, low pressure, varying oxygen fugacity and on bodies with varying compositions. As increasing knowledge points to the Earth and other terrestrial bodies being formed from already differentiated planetesimals it is essential that we understand what these planetesimals looked like in order to fully understand how the Earth and other terrestrial planets formed.

The principle of using stable isotopes to probe the bulk chemical composition of planets lies with the combination of isotope fractionation and sequestration of elements in unsewn reservoirs like the core. Isotope fractionation will exist between phases with distinct bonding environments (e.g., core and mantle), and separation of elements between reservoirs manifests this fractionation.

A wide range of non-traditional stable isotope systems have been measured in differentiated materials from our solar system: e.g. Mg, Fe, Si, Ca, Cu, Ni, Sr, Cr and Cd. Each study begins with measurements to establish a chondritic reference frame, the starting isotopic ratio for the element of interest. Next, the isotopic ratios are measured in natural samples or experiments. Then an argument is made about the physical and chemical conditions that existed on the planetesimal that the stable isotopes are tracing. In many of these cases, there is still considerable debate over interpretation of the data and/or if the isotope variations are definitively linked to planetary differentiation/evolution processes.

Stable isotopes can fractionate through either equilibrium or kinetic processes. During the differentiation process, the molten iron metal will alloy with other elements on its route to the center of the planetary body. This is thought to have occurred at equilibrium, however, it is entirely possible that as this was happening, the planetary body was also evaporating at the surface and escaping from the early atmosphere. Determining how all these processes affect isotope ratios is imperative for determining how the isotope ratios are interpreted.

Methods: To fully understand how stable isotopes can probe planetary differentiation and evolution, we have conducted piston cylinder [1,2] and diamond anvil cell experiments [3], calculated theoretical fractionation factors [3], analyzed meteorite samples [4], and calculated the effects of volatilization on isotope ratios [5]. We have begun by focusing on the major elements: Fe, Mg and Si.

Results: Our experimental results suggest that there is an isotopic fractionation factor associated with equilibrium metal-silicate fractionation that is dependent on composition, pressure, and temperature. Experiments conducted in the Fe isotope system display large variations that will be compared with differentiated meteorites, as well as literature data from samples from Earth’s mantle. Further, our calculations suggest that isotopes are fractionated during evaporation from the surface of a molten planetesimal, as well as through Jeans escape from the early atmosphere. These calculations will be used to explain recent Mg and Si isotope ratios measured in meteorite samples [6]. Finally, our analyses of pallasite meteorites suggest that only the metal and troilite equilibrated whereas the iron in the olivines did not due to slower diffusion coefficients.

Discussion: This talk will focus on how stable isotope ratios can inform us about the differentiation of planetesimals. Unlike radiogenic isotopes, there are many processes which will fractionate stable isotopes so it is imperative that experiments be conducted to determine fractionation factors at a range of conditions applicable to planetary formation scenarios. By conducting experiments, analyzing natural samples, and then modeling the results, we can begin to unravel the conditions under which these bodies evolved.

Si isotopes in enstatite chondrites: Implications to accretion and differentiation event of the Earth J. Sikdar1,2,3, and V. K. Rai1,3, 1Physical Research Laboratory, Ahmedabad, India, 2Institut für Geologische Wissenschaften, Freie Universität Berlin (*jinia@zedat.fu-berlin.de), 3Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, USA.

Introduction: Si is one of the most abundant elements of the solar system that participates in almost all dominant geo- and cosmochemical processes. As such, the isotopic distribution of Si among various solar system materials places important constraints in tracing the building blocks of planets. Of all major chondrite groups, enstatite chondrites (EC) display the closest composition relative to the silicate reservoir of Earth (Bulk Silicate Earth, BSE) with respect to a number of isotope systematics with the exception of Si [1-4].

However, enstatite chondrites, being formed under highly reducing conditions, are the only group of planetary bodies that display a bimodal distribution of Si between metals and silicates [5]. It has been documented that Si isotopes are distributed heterogeneously within different components of EC [6]. Therefore, an accurate determination of the extent of Si isotope heterogeneity within EC is important before deeming off EC as an important precursor material of Earth. To do so, we have carried out high precision Si isotope analyses in purest possible micromilled components of EC using Neptune MC-ICPMS at PRL, Ahmedabad, India [7].

Results: We find that the metals of EC are enriched in extremely lighter isotopes of Si (going upto ~ -7‰) whereas the silicates possess heavier δ30Si, which is strikingly similar to BSE.

Discussion: Based on HF-W systematics in EC and thermodynamic constraints on condensation sequence of minerals at high C/O ratio, it is known that metals condense earlier than silicates under reduced conditions [8-9]. Lending support from this fact and the Si isotope distribution within EC, it can be said that nebular fractionation associated with alteration of the residual silicate gas reservoir in heavier Si isotopes due to partitioning of extremely light isotopes of Si in early condensed metals of reduced EC/Earth accreting region can best explain the observed offset in δ30Si between BSE and chondrites.

The similarity in δ30Si between the silicate reservoir of Earth (i.e., BSE) and the silicate fractions of EC provide a strong suggestion for the origin of ECs and the Earth in a narrow isotope reservoir of solar system. Also, it indicates that the two planetary bodies have undergone similar history of isotope evolution. Therefore, based on this recent isotope results, it can be suggested the Earth was formed through rapid accretion of reduced planetesimals. The primary differentiation of Earth had happened when partial melting of embryonic Earth led to rapid segregation of metals in the center to form the proto-core owning to lack of equilibrium between metals and silicates. This implies that a major fraction of Earth’s core was already formed before the silicates had started to accrete and form BSE. To explain the superchondritic Mg/Si ratio of BSE, the concept of gradual oxygenation of nebula has to be invoked.

Use of Meteorite Names: PCA 91461, LAR 06252, MIL 07028, Y691 and Parsa

SOURCE REGIONS FOR THE EARTH’S MAGNETIC FIELD DURING THE FIRST BILLION YEARS.
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**Introduction:** Paleomagnetic evidence suggests Earth maintained a magnetic field since 3.2Ga [1], and claims exist for even as early as 4.2Ga [2]. However, revised values for the thermal conductivity of Fe at core conditions [3] pose considerable challenges for conventional mechanisms of generating a dynamo over Earth’s history as the larger adiabatic heat flows imply rapid secular cooling, a young (i.e. 500 Myr) inner core, and thermal evolution models with supersolidus mantle temperatures [4]. This has lead to proposals for alternative dynamo sources including a dynamo generated in a long-lived basal magma ocean [5], and compositional buoyancy driven by exsolution of Mg [6,7] or Si [8] from the core into the mantle.

**Early Dynamo Sources:** It has been proposed that following the Moon-forming impact, the Earth becomes molten and as such high T (\textgtrsim5000K), Mg and/or Si can partition into the metallic core and replace \textasciitilde3% of the core’s mass. After sufficient secular cooling of the core, Mg will precipitate and provide a compositional power source for a core dynamo. The exchange coefficients measured in diamond anvil cell experiments were across an interface between large, well-mixed reservoirs of liquid metal and liquid silicate [6]. Thus, these results are only applicable to scenarios in which a liquid core is exchanging with a molten silicate mantle, such as the proposed basal magma ocean [9]. Thermal evolution models that appeal to these exsolution mechanisms require a basal magma ocean in order to be internally consistent with the reported exchange rates. Further, previous exchange rates were reported assuming a pyrolitic mantle composition for the liquid silicate [6].

**Delayed Mg Exsolution (Mg-X):** If the mantle had solidified by the time the core had cooled sufficiently for exsolution to begin, the assumption of a well-mixed pyrolitic reservoir is invalid, and a layer of pure Mg sediments under the core-mantle boundary would form. The equilibrium concentration in the core would not be reached until the core had cooled by at least a further 500-600C which would significantly delay the onset of exsolution. For the two Moon-forming impact scenarios considered, a Mars-sized impactor [9] and a fast-spinning impactor [10], the onset for exsolution is delayed from 3.4 to 2.1 Ga and from 2.2 to 1.1 Ga, respectively. Both cases of the pyrolitic mantle and pure Mg sediment layer have onset times well after the earliest evidence of a magnetic field. Thus, alternative dynamo mechanisms should be considered. We will present hybrid models of dynamo source regions for the first billion years (Fig 1) that include the basal magma ocean dynamo (BMOD) [5] which can reconcile thermal evolutions for the mantle and core as well as Mg exchange rates.


![Figure 1: Possible sources of dynamo generation over Earth history (from left to right). Hadean: BMOD only; Archean: BMOD combined with Mg-X; Proterozoic: Mg-X and core cooling; Modern: Inner core growth](image-url)
PALEOMAGNETIC RECORDS OF ANCIENT CORE DYNAMOS. S. M. Tikoo¹, ¹Department of Earth and Planetary Sciences, Rutgers University, Piscataway Township, NJ 08854 (sonia.tikoo@rutgers.edu).

Introduction: Dynamo magnetic fields are generated by advection of molten metal within the cores of rocky planetary bodies. This advection may be driven by thermal core convection, thermochemical convection sustained by inner core crystallization, or mechanical perturbation of core fluid. Therefore, paleomagnetic records of ancient dynamos shed light on the energy budgets and thermal evolution of differentiated bodies. Records of ancient dynamo fields have been identified within rocks from the Moon [1,2], Mars [3], and a number of small bodies. Here we detail how magnetic studies of Apollo samples have permitted the development of a lunar paleointensity record that spans at least two billion years (Fig. 1). We also discuss how similar work on meteorites has allowed paleomagnetists to investigate planetesimal differentiation, dynamo generation, and other early solar system processes.

The lunar dynamo: Paleomagnetic studies indicate that the Moon generated a core dynamo between at least 4.25 and 2.5 billion years ago (Ga) (Fig. 1) [1,2]. It is unclear when the dynamo ceased, but it may have persisted until ~1 Ga or beyond [4]. A conundrum arising from the paleointensity data is that lunar surface fields were apparently ~78±43 μT between ~3.85-3.56 Ga, ~1 order of magnitude higher than what scaling laws suggest can be produced by a convective dynamo operating within the Moon. These paleointensity results have motivated investigations into whether an exotic mechanical dynamo could have produced the strong fields inferred for the period ~3.85-3.56 Ga, as well as efforts to estimate the longevities of thermochemically convective dynamos operating within the Moon [1,2].

Most of the lunar paleointensity values shown were obtained using non-heating methods that have a factor ~2 uncertainty [1,2]. More accurate paleointensities may be obtained by a thermal method that involves progressively heating samples to high temperatures in an atmosphere that reproduces the reducing environment of the Moon and prevents thermochemical alteration of FeNi magnetic grains within lunar rocks [5]. Such heating experiments have been successfully applied to an Apollo sample and mare basalt analogs [4,5], and may be used in the future to obtain more accurate paleointensities from lunar rocks and metal-bearing meteorites.

Meteorite magnetism: Paleomagnetic studies have determined the paleointensity and lifetime of solar nebula fields in the planet-forming region [6,7]. They have also enabled timing of the onset and/or cessation (as well as the paleointensity evolution) of core dynamo fields on multiple bodies [7-9] (Fig. 2). Potential dynamo field records within some carbonaceous chondrites suggest that these meteorites may have originated from partially differentiated bodies [10,11], although this interpretation has been debated. In aggregate, recent paleomagnetic studies have provided a great deal of insight into processes occurring within the first billion years of solar system history.

Fig. 2. Core dynamo lifetimes of rocky solar system bodies inferred from paleomagnetism and crustal magnetism studies.

A MUDBALL MODEL FOR THE EVOLUTION OF CARBONACEOUS ASTEROIDS. B. J. Travis1 and P. A. Bland2,3,4Planetary Science Institute, 1700 E. Ft. Lowell, Suite 106, Tucson, AZ 85719, USA, btravis@psi.edu; School of Earth and Planetary Science, Curtin University, GPO Box U1987, Perth, WA 6845, Australia, p.a.bland@curtin.edu.au.

Introduction: A number of numerical models have been developed to understand the evolution of carbonaceous asteroids. The initial state for these models involves anhydrous coherent rock reacting with water. But there is no a priori reason why nebular fines, ice, and chondrules would be lithified before aqueous alteration. Recent work have explored the effect of removing the assumption of lithification – the so-called ‘mudball’ model [1-3].

The model: In this study we explore this concept with the MAGNUM numerical simulator, previously used to model hydrothermal and chemical evolution of consolidated carbonaceous chondrite parent bodies [4,5]. New features include particle transport using Stokes-Rubey settling [6,7], minimum porosity from packing models, mud viscosity, and serpentinitization. Model asteroids are initially unconsolidated mixtures of coarse particles (chondrules) and mud (initially a uniform mix of fines and ice). The code tracks chondrules. Dimensionless tracer particles scattered throughout the mud also allow us to track movement, temperature and water/rock (WR) ratio - dimensionless mud ‘grains’ - as they evolve within the body over time. Here we focus on results for CM chondrites.

Input parameters: Initial abundance of radioisotopes, bulk chemistry, and the range of plausible WR ratios for a specific chondrite group are drawn from the literature. Other key factors are accretion time, parent body diameter, and chondrule size frequency distribution (SFD).

Accretion time. Geochronology of components in chondritic meteorites constrain accretion time: chondrule ages give an upper limit; ages for alteration products a lower limit. Mn-Cr ages for carbonates in CMs and Cls, supplemented with thermal modelling [8,9], indicate an accretion age for the CM and Cl meteorite parent bodies of 3-4Myr, a time range common for other chondrite types.

Parent body diameter. Studies of the SFD of main belt asteroids suggest that bodies >120km diameter represent an accretionary population, and that the planetesimal formation process favored the creation of bodies >100km [10].

Chondrule SFD. We include a variety of SFDs in the mudball model for each simulated body, tailored to specific chondritic parent bodies based on literature data for the relevant meteorite type [11].

CM chondrites. Almost all of these rocks appear to have experienced alteration over a narrow temperature range, and at relatively low temperatures (<150°C). Model results show a similar feature. Mud convection moderates internal temperature, and reduces variation in temperature throughout. Bodies accreting at 3-3.5Myr, with 100-200km diameter, and at bulk WR=0.6-1.0, all show similar peak T (<150°C). More than 95% of the asteroid beneath the ice shell experiences alteration over only a 75°C temperature range.

By tracking the evolution of dimensionless tracer particles we can explore another feature of CM petrography: Large-scale homogeneity vs fine-scale chemical and isotopic heterogeneity in these rocks [12-15]. This seems difficult to achieve in a lithified rock where neighboring components could be expected to witness similar conditions. We find that a single mud grain tracer might circulate throughout the body, from core to just beneath the ice shell. Grains that might be adjacent at the end of convection could nevertheless experience a wide range of T and WR conditions.

Conclusions: An unconsolidated mudball model may offer a general solution to the evolution of carbonaceous asteroids. The model is not finely tuned to generate a specific outcome, but we observe outcomes that are close to meteorite petrography. We are extending the mud-ball model to other chondrite groups [16]. We have also applied the model to evolution of Ceres assuming it is a CM/CI-like body [17].

LATE PLANETARY DIFFERENTIATION: LUNAR ‘KREEP’ AS A LOCAL PRODUCT.  A. H. Treiman, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058 <treiman@lpi.usra.edu>.

Within the lunar magma ocean (LMO) model of lunar history, the last differentiate of the LMO is the source of the lunar KREEP chemical component: strongly enriched in K, rare earth elements, P, etc. [1-4]. KREEP was originally inferred to be global in extent, it is actually restricted to the Imbrium basin and its ejecta [5]; SPA basin materials are somewhat enriched in KREEP elements, but different from Imbrium KREEP (iKREEP) [6]. The question is whether KREEP is so extensive and invariant to be consistent with a global process, or is better explained as local differentiates.

Sample Analyses: iKREEP is a chemical component discovered in Apollo returned samples, and has quite consistent element abundance ratios across the lunar nearside, Fig. 1 [3,4]. However, a few materials have ratios distinct from iKREEP, like samples 722x5 (A17, station 2, Boulder 1 [8]) and VHK basalts [9], Figs 1-3.

Few lunar meteorites (which sample the whole lunar surface) are enriched in incompatible elements, although SaU169 is iKREEP-rich (Fig. 1). The Dho25 meteorite and its pairs [10] are suggested to hail from the South Pole-Aitkin Basin [11]. These samples have incompatible element abundance ratios distinct from iKREEP (Figs 2,3), and are consistent with orbital inferences about SPA [6].

Basins & Ejecta: iKREEP is spatially restricted to the Imbrium Basin and its ejecta, and the SPA basin has a distinct KREEPy signature. However, orbital mapping of abundances of Th, U, and K do not show strong enhancements/enrichments around other major basins: Crisium, Orientale, Moscoviensi, and maybe Serenitatis & Tranquilitatis [5,6,12]. These absences of KREEP signatures suggest that there was no KREEP (or urKREEP) in those basins’ targets, and thus that KREEPy material was not a globally distributed (or that the basins’ excavations were extremely shallow). Combined with the ranges of element abundance ratios in lunar samples, it seems most likely that KREEPy materials are local products of igneous differentiation, and not remnants of a global LMO.

Lunar anorthositic rocks, the main constituents of the lunar highlands, have long been considered products of a global-scale lunar magma ocean, LMO \([1-3]\). In short, the LMO theory posits that, early in the moon’s history, its bulk or substantial portions of it were molten, and that the moon’s anorthositic crust represents a flotation cumulate of plagioclase on that ocean. Plagioclase crystallizes late from the LMO, and thus is associated with highly ferroan minerals. The last LMO magma is rich in incompatible elements, and is the source of the KREEP component. After LMO crystallization, the mantle overturns, mixing late and early mafic cumulates; these are the sources mantles for mare basalts and Mg-suite plutonic rocks.

However, evidence inconsistent with this simple LMO paradigm has accumulated, and suggests that the paradigm needs significant modification or abandonment. Here, we review some of the problems with the LMO hypothesis.

**Magnesian Anorthosites.** The LMO hypothesis requires that lunar anorthosites be ferroan, as they form towards the end of LMO crystallization. However, magnesian anorthositic rocks are known in the Apollo collection \([4,5]\), and are common as clasts in lunar meteorites \([6-10]\). These rocks have no place in a simple LMO model; some could be related to post-LMO Mg-suite magmatism, but others lack the KREEP component enrichment typical of the Mg-suite.

**Plagioclase Compositions:** Trace element abundances in anorthosite plagioclase can be interpreted to derive abundances in the parent magma. From those, parent magmas of ferroan and magnesian anorthosites formed from magmas with a factor of 10 range in REE contents \([11,12]\). This heterogeneity suggests that the anorthosites, ferroan and magnesian, could not have each crystallized from a common magmatic source. This inference is not consistent with the simple LMO hypothesis.

**Radiometric Ages:** Radiometric ages of lunar rocks present at least three distinct problems for the LMO hypothesis: the ages of ferroan anorthosites; the ages of Mg-suite plutonic rocks; and the age of mare basalt source region. In the LMO model, the anorthositic crust formed very early in lunar history, however radiometric ages for anorthosites range from 4.56 to \(~4.3\) Ga \([13,14]\), which is rather young.

In the LMO model, the Mg-suite plutonic post-date ferroan anorthosite, because they are rich in KREEP component which formed after the anorthosites \([15]\). However, the ages of Mg-suite rocks overlap those of ferroan anorthosite, being from \(~4.45\) to \(~4.2\) Ga \([14]\).

In the LMO model, the source regions for mare basalts are generated by mantle overturn after anorthosite formation, mixing early magnesian cumulates, late ferroan cumulates, KREEP, and Ti-rich cumulates \([3]\). Thus, the differentiation age of the mare basalt source regions should be younger than that of the anorthosites. However, they have the same radiometric age, which is inconsistent the LMO idea “… unless the anorthosites are also a byproduct of overturn” \([16]\).

**Serial Magmatism:** Given these problems with the LMO paradigm, we suggest again that current lunar crust is better explained by serial magmatism: formation as mass of overlapping rising anorthositic diapirs derived from large basaltic magma chambers intruding an (undefined) primary crust \([17,8,9]\). This idea accommodates the ranges of compositions and ages of anorthosites (though not necessarily explaining them). The similar radiometric ages of anorthosites and the mare basalt sources is understandable if the sources were formed from overlapping descending diapirs of mafic/ultramafic composition \([18]\), complementary to the rising anorthosite diapirs \([9,16,19]\).

**References:**

**Introduction:** Tracing the Earth’s differentiation history is hampered by the paucity of Archean rocks. Fortunately, short-lived isotopic systems such as the $^{142}$Sm-$^{144}$Nd system can provide evidence of early differentiation events. As Sm and Nd have slightly different geochemical behaviors during mantle melting, any early formed crust will have a lower Sm/Nd than the residue mantle, and as such the two reservoirs will evolve to different $^{142}$Nd compositions with time during the lifetime of $^{146}$Sm (~500 million years, Ma). Today, the modern mantle has a uniform $\mu^{142}$Nd of 0±4, indicating that the accessible mantle has become homogenized with respect to $^{142}$Nd since the extinction of $^{146}$Sm. However, some of the oldest rocks on Earth at ~3.9 billion years (Ga) have an anomalous $\mu^{142}$Nd signature compared to the modern Earth [1, 2, 3, 4, 5], while only a very limited number of Neoarchean rocks are anomalous [6]. This late anomaly has been interpreted to reflect an inefficient homogenization of the mantle during the Archean, in the absence of mobile lid plate tectonics. [6]. On the other hand, Paleaoarchean rocks display a large variation in $\mu^{142}$Nd, from −18.0 to +16.5 [3, 7]. The large variation in $\mu^{142}$Nd positive values has been interpreted as either reflecting a heterogeneously differentiated Earth, or a heterogeneously remixed Earth [2].

In order to understand the implications of those two possibilities in terms of terrestrial global differentiation, we have expanded the database of Archean samples by analyzing rocks from other poorly-investigated Archean terranes from around the world, such as the São Francisco (Brazil) and West African cratons. We plan to also analyze samples from the Lewissian terrane in Scotland and the Yilgarn craton in Australia.

**Results:** No resolvable $\mu^{142}$Nd anomaly from modern day terrestrial was obtained on ~2.9 Ga TTG and 3.3 Ga meta-basalts from the West African Craton (Figure 1). Preliminary results from ~3.3 Ga felsic rocks from the São Francisco craton also display no resolvable anomalies (Figure 1).

**Discussion:** Short-lived radionuclides are unique in their ability to provide information about the timing and extent of differentiation of the early Earth. To date, the majority of large resolvable anomalies (in both $^{142}$Nd and $^{182}$W) have been confined to the Superior and North Atlantic Cratons. Our results on geographically diverse Paleo- and Mesoarchean samples yield no resolvable anomalies from the modern terrestrial mantle. This highlights the geographically constrained extent of the anomalous Archean mantle characterized by a higher Sm/Nd very early in Earth’s history. Such a constrained area on the modern Earth may be pure chance but it could also be a direct result of early Earth differentiation. While we cannot rule out a heterogeneous remixing of the mantle, our preferred interpretation for this restricted geographical spread is that the early Earth differentiated heterogeneously. This implies the Archean Earth’s mantle was made of two different domains, with contrasting differentiation histories. As such, the Acasta, Isua and Nuvvuagittuq Archean terranes of the Superior and North Atlantic cratons are the last remaining remnants of one of those early differentiated portions of the Earth.

**Conclusions:** No resolvable $\mu^{142}$Nd anomaly was detected in Paleo- and Mesoarchean rocks of the West African and the São Francisco cratons. This emphasizes the lack of significant $\mu^{142}$Nd anomalies outside of North America and Greenland. As such, it can be envisaged that the early Earth was composed of at least two distinct domains, with only one preserving evidence of early silicate differentiation.


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**Figure 1:** $\mu^{142}$Nd (relative to JNd) of ~2.9 Ga TTG and 3.3 Ga meta-basalts from WAC, and ~3.3 Ga felsic intrusives from the São Francisco craton. The grey box represents the external reproducibility of the terrestrial standard JNd. All samples are within error of modern day terrestrial.