Before the Moon

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Workshop on the first 50-100 Myr of the solar system

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Earth-Life Science Institute (ELSI) Tokyo, Japan

EARTH - LIFE SCIENCE INSTITUTE

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MONDAY

08:45-08:50 Welcome (**Hirose**)

08:50-09:00 Introduction (**Mojzsis**)

Session: First solar system solids and formation timescales (Chair: **Mojzsis**)

09:00-09:35 **Huss:** The raw materials for making the solar system

09:35-10:10 **Ireland:** Chronology of the early solar system and implications for processes

10:10-10:45 **Chaussidon:** Constraints on timing and processes from dust to chondrules

Break 15mn

11:00-11:35 **Russell:** The formation environment of chondrules and calcium aluminium rich inclusions

11:35-12:10 **Bouvier:** Chronology of early solar system materials and implications for the protoplanetary disk

12:10-13:30 Lunch

Session: Accretionary processes: From dust and planetesimals to planets (Chair: **Russell**)

13:30-14:04 **Ciesla:** Dust growth and its effects on transport in disks

14:05-14:40 **Ida:** Formation of planetesimals

Break 20mn

15:00-15:35 **Morris:** Models for chondrule formation in the early solar nebula

15:35-16:10 **Nimmo:** Accretion, mixing and differentiation of planetary bodies

16:10-16:45 **Brasser:** The cool and distant formation of Mars

Break 15 mn

17:00-18:30: Open Forum: Questions – Discussion – New ideas

TUESDAY

Session: Isotopic variations in chondrules and planetary materials (Chair: **Bouvier**)

08:45-09:20 **Qin:** Cr isotope systematics of chondrules

09:20-09:55 **Alexander:** The link between chondrule formation and chondrite accretion

09:55-10:30 **Yurimoto:** Evolution of planet-forming components in the first millions of years of solar system formation

Break 15mn

10:45-11:20 **Fischer-Gödde:** Establishing genetical links among solar system materials using nucleo-synthetic Ru and Mo isotope anomalies

11:20-11:55 **Carlson:** Controls on terrestrial planet composition(s)

12:00-13:30 Lunch

Session: Pebbles vs. planetesimals; HSE geochemistry (Chair: **Ida**)

13:30-14:05 **Kretke:** Forming the solar system from pebbles

14:05-14:40 **Matsumura:** The effects of dynamical evolution of giant planets on the elemental abundances of terrestrial planets

Break 20 mn

15:00-15:35 **Day:** Distribution of highly siderophile and volatile elements in proto-earth materials

15:35-16:10 **Yin:** Enstatite chondrites, the Earth-like reservoir and the timing of gap opening in the early solar nebula by Jupiter formation

Break 20 mn

16:30-18:30 Open Forum: Questions – Discussion – New ideas

WEDNESDAY

Session: Evening of the Moon-forming event and beyond (Chair: **Brasser**)

08:45-09:20 **Boyet:** Magma oceans in the Earth-Moon system

09:20-09:55 **Hernlund:** What do we really know about magma ocean oxygen fugacity?

09:55-10:30 **Mojzsis:** Evolved crusts in dynamically ‘hot’ planetary embryos

Break 15mn

10:45-11:20 **McKeegan:** Oxygen isotopes on an old Moon

11:20-12:00 Open Forum: Questions – Discussion – New ideas

12:00-13:30 Lunch DISASTER DRILL 12:15-13:00

Group formation – writing (13:30-18:00)

THURSDAY

Group formation – writing (09:00-12:00)

12:00-13:30 Lunch

Group formation – writing (13:30-16:00)

THE RAW MATERIALS FOR MAKING THE SOLAR SYSTEM. Gary R. Huss, Hawaiʻi Institute of Geophysics and Planetology, University of Hawaiʻi at Mānoa, 1680 East-West Road, Honolulu, HI 96822, ghuss@higp.hawaii.edu.

Introduction: The solar system formed through collapse of a dense core in a cold molecular cloud. In order to truly understand how this process produced the solar system that we inhabit, we need to understand the raw materials that were present in the molecular cloud and were processed in the solar system to make the solar-system bodies. I will discuss each of the following topics.

Stellar Nucleosynthesis: Except for H and He, the elements that make up our solar system were produced in stars. We have a reasonable understanding of the processes of stellar nucleosynthesis and can describe the products of all types of stars. This understanding is buttressed by observations of presolar grains that formed in the ejecta of dying stars and that carry snapshots of the elements and isotopes that were being ejected from those stars [1]. We have also been able to build up a general picture of galactic chemical evolution [2].

Journey to the Solar System: Upon ejection from dying stars, a fraction of the newly synthesized elements condense into mineral grains such as those we recover from meteorites. The rest are ejected as gas [3]. In interstellar space, grains are subjected to supernova shocks and intense radiation that can vaporize them. Although the destruction rate is a matter of debate, observed depletions of dust-forming elements in the ISM require evaporated elements to accrete onto pre-existing dust grains in cold clouds [3]. The fraction of crystalline silicates in the interstellar medium is low (<2.2% [4]), implying either amorphization of crystalline grains or non-equilibrium recondensation of evaporated dust. Ices also accrete onto pre-existing grains, and radiation-induced reactions produce organic compounds on grain surfaces [5]. The thermal stability of amorphous and cold-acreted material and its role in generating elemental fractionations in the solar system is not understood.

Star Formation: From studies of solar system objects and observations of young stellar systems, we have a general picture of how stars form. The dense core collapsed to a protostar surrounded by a rotating disk of gas and dust. The planets, asteroids, and comets formed from this disk. The new Atacama Large Millimeter/submillimeter Array (ALMA) is revealing the structure of newly forming stellar systems. There is evidence of grain growth and increasing crystallinity with time in young stellar systems, though the details are not yet clear [6]. The timescale for transitioning from a collapsing core in a molecular cloud to a star with only remnants of an accretion disk is ~10 million years [7].

Cosmochemistry: Although processes in the early solar system will primarily be discussed by others, there are important observations about early solar system bodies that directly reflect the nature of the materials in the Sun's parent molecular cloud. Recent measurements of the isotopic compositions of N, O, and noble gases in the solar wind from the Genesis Mission [8-11], combined with our knowledge of the isotopic compositions of H, C, N, O, and noble gases in solar system materials show that there is a clear dichotomy in isotopic composition between solar-system solids (represented by terrestrial planets, asteroids, and comets) and solar-system gas (which dominates the composition of the Sun). The solids are isotopically heavier. Models have been produced to explain this dichotomy for each element, but there is no general model. The underlying cause of this dichotomy is related to the fact that all of these elements existed in both gas and solid phases in the parent molecular cloud, and the isotopic differences reflect the distinct histories of gas and solids [12].

Differential destruction of the most reactive carbon-rich presolar grains among the least metamorphosed chondrites correlates with the depletions of moderately volatile elements of the host meteorites [13,14]. These correlations imply that the thermal processing that produced the bulk compositions of different classes of chondrites also affected the presolar grains. The bulk compositions represent the whole meteorite, while the presolar grains are found only in the matrix. The correlation implies that the processing that produced the bulk compositions and depleted the reactive presolar grains occurred prior to chondrule formation and affected most of the accreted material.

Isotopic anomalies in rock-forming elements such as O, Cr, and Ti are ubiquitous among chondrites [15-17]. Oxygen compositions are widely used to classify meteorites [15]. Other elements could also be used, except that measurements are so difficult. There are correlations between anomalies in different elements that appear to be consistent with partial separation nucleosynthetic components [16]. Volatility-based separation has been proposed as a mechanism to separate nucleosynthetic components. Variation in initial $^{26}Al/^{27}Al$ in different objects could also be due to partial separation of components containing “new” Al, which has ^{26}Al, and “old” Al, in which the ^{26}Al has decayed away [17].

Summary and Conclusions: Observations of solar system materials show that the history of the raw materials that became the solar system can still be read in solar system materials. The formation of the solar system did not erase that history. We do not yet have a clear picture of presolar history of the raw materials that made up our solar system. But if we recognize the broad outlines of that picture, we can fill in the details with the results of our research.

References: [1] Zinner E. (2014) in *Meteorites and Cosmochemisl Processes* (A. M. Davis, ed), Vol. 1, *Treatise of Geochemistry* (H. D. Holland & K. K. Turekian), pp. 181-213. [2] Spitoni E. and Matteucci (2011) *A&A 531*, A72. [3] Dwek E. (2016) *Astrophys. J. 825*, 136. [4] Kemper F. et al. (2005) *Astrophys. J. 633*, 534. [5] Li A. and Greenberg J. M. (2002) *Astrophys. J. 577*, 789-794. [6] van Boekel R. et al. (2005) *A&A 437*, 189-208. [7] Hernandez J. et al. (2007) *Astrophys. J. 662*, 1067.[8] McKeegan et al. (2011) *Science 332*, 1528-1532. [9] Marty B. et al., (2011) *Science 332*, 1533-1536. [10] Heber V. S. et al. (2009) *GCA 73*, 7414-7432. [11] Meshik A. et al. (2014) *GCA 127*, 326-347. [12] Huss G. R. (2012) *MAPS 47*, Abstr #5294. [13] Huss et al. (2003) *GCA 67*, 4823-4848. [14] Huss G. R. (2004) *Ant. Met. Res. 17*, 132-152. [15] Clayton R. N. (2003) *Space Sci. Rev. 106*, 19-32. [16] Trinquier A. et al., (2009) *Science 324*, 374-376. [17] Van Kooten E. M. M. E. et al. (2016) *PNAS 113*, 2011-2016.

CHRONOLOGY OF THE EARLY SOLAR SYSTEM AND IMPLICATIONS FOR PROCESSES. T. R. Ireland[1] R. Salmeron[2], and Y. Amelin[3], [1]Planetary Science Institute and Research School of Earth Sciences, The Australian National University, Canberra ACT2601, Australia (trevor.ireland@anu.edu.au), [2]PSI and Mathematical Sciences Institute, ANU, Canberra ACT2601, Australia (raquel.salmeron@anu.edu.au). [3]PSI and RSES, ANU, Canberra ACT2601, Australia (yuri.amelin@anu.edu.au)

Introduction: The meteoritic record of the early solar system covers only around 10 million years (Myr) around 4,567 Myr ago. These ages likey reflect infall of the molecular cloud through to the later stages of planetary accretion and differentiation. The Nebula Stage includes formation of refractory inclusions and chondrules. This epoch is characterized by local extreme heating, either in precursors or in the melting of the objects themselves. Extremely high temperatures are required to cause fractional condensation of rare earth elements, although the inclusions themselves likely reflect melting and evaporation at lower temperatures [1]. The Planetary stage involves the accretion of planetesimals to sizes where planetary melting and differentiation can occur.

Chronology: Determining the chronology of the early solar system is made difficult because of the short duration of the main nebula and planetary phases, but also the limitations of chronomaters available [2]. Absolute ages are provided by the coupled U-Pb decay schemes. The age of the solar system is around 4,567 Myr as defined by $^{235}U/^{238}U$ fractionation corrected $^{207}Pb/^{206}Pb$ ages of refractory inclusions [3,4]. Chondrules range in age from a similar formation time as refractory inclusions through to around 4,564 Myr. Within the age range of chondrules the oldest planetary differentiates are found, viz. angrites which show ages from 4,565 to 4,558 Myr [5].

The decay products of short-lived radionuclides such as ^{26}Al, ^{53}Mn, ^{182}Hf, also provide age constraint in nebula and planetary phases. ^{26}Al-^{26}Mg is widely used where high Al/Mg phases are available, but model ages based on $^{26}Mg_0$ can also be used to verify the system behavior of ^{26}Al-^{26}Mg where high Al/Mg phases are not available. Model ^{182}Hf-^{182}W ages are used to constrain planetesimal core-formation on the basis that W is strongly fractionated in to the metal core and Hf resides in the stony mantle. Such ages are typically within 1.5 Myr of refractory inclusion formation [6].

What are we dating?: The nature of the processes active in the early solar system and in particular the processes responsible for setting radioisotope clocks is possibly quite different to that envisaged from terrestrial systems [2]. While the closure of the U-Pb systems both in refractory inclusions and angrites appears to be associated with rapid solidification, there remain potential discrepancies in different chronometers when anchored to a specific closure. The Hf-W system appears anomalous in that planetesimal core formation appears to be occurring at the same time as refractory inclusion formation. This places extreme constraints on the growth of planetesimals relative to t_0.

Processes: The early solar system is envisaged as an accreting disk of gas and dust falling in to the Sun. However, the context of material processing within this paradigm is fragmented at best. We have materials processed at high temperature, but we lack detail as to where this is occurring. We have some degree of detail in terms of chronology, but we lack details of the placement, as well as the processes. We have been exploring the role of disk winds in causing heating and high temperature fractionations in the early solar system [7]. Disk winds offer the possibility of thermal processing at distances similar to the accretion distances of asteroids, while providing a transport mechanism taking inner solar system materials to the outer disk. A key feature of this type of model is the potential for devolatilisation and material processing in the inner solar system and its potential for producing metal and silicate unmiuxing in the early solar system. As such, the Hf-W model ages of metal could be produced as a nebula fractionation rather than planetary.

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CONSTRAINTS ON TIMING AND PROCESSES FROM DUST TO CHONDRULES. M. Chaussidon, Institut de Physique du Globe de Paris, 1 rue Jussieu, 75238 Paris Cedex 05, France (chaussidon@ipgp.fr)

Introduction:

Minerals directly issued of condensation from the nebular gas are very rare in chondritic meteorites. Refractory inclusions are the objects which are the most straightforward to link to a condensation origin of their precursors, even though their petrography and isotopic composition clearly point to multi-stage nebular histories involving remelting and evaporation/condensation, an extreme being the case of FUN inclusions [1]. A canonical condensation sequence type of scenario for forming dust from nebular gas predicts that the dominant dust condensed at temperatures higher than 900 K is a mix of forsterite and enstatite [2]. The dominant component of ordinary and carbonaceous chondrites is chondrules, among which reduced type I chondrules containing various proportions of fosterite and enstatite are by far the most abundant type of chondrules. In type I chondrules, relict forsterites that survived to the chondrule forming process, can be identified from their oxygen isotopic composition [3, 4]. Despite various origins are possible for chondrules, from nebular to planetary scenario, oxygen and magnesium isotopic compositions bring clear constraints on the origin and history of their precursors, and thus of nebular dust.

^{26}Al constraints on the timing of formation of chondrule precursors: ^{26}Al-^{26}Mg systematics of chondrules can be used to constrain the age of the last melting event but also the age of the precursors by combining bulk ^{26}Al-isochrons and mineral ^{26}Al-isochrons. Bulk ^{26}Al-^{26}Mg data show that all chondrules precursors formed contemporaneously with CAIs up to 1.5(±0.2) Myr later [5]. At variance chondrule last melting events extend up to 3 to 4 Myr after CAIs [5, 6 and refs therein].

Oxygen isotope constraints on the origin of chondrule precursors: The distribution of the three-oxygen isotopic compositions of bulk Mg-rich porphyritic chondrules and of their individual minerals on a linear trend between the so-called YR and CCAM lines is a signature of high-temperature interactions during the formation of chondrules between (i) a gas enriched in SiO and depleted in ^{16}O and (ii) solid precursors of forsteritic composition and variously enriched in ^{16}O (along the CCAM line) [7]. Depending on the dust-gas ratio, pyroxene and olivine in chondrules can either be at oxygen isotopic equilibrium or show various desequilibrium [7]. Thus the chondrule data point to various dust-gas ratio in the chondrule forming regions and to the fact that forsteritic precursor dust had variable ^{16}O contents and was distributed on the CCAM line which is considered as being a "secondary" line.

Evidences for the formation of some type I chondrules in very oxidizing environments: Some Mg-rich type I porphyritic chondrules contain sulfide-associated magnetites (SAMs) of magmatic origin, resulting from the segregation from chondrules' silicate melts of immiscible FeS melts having various amounts of dissolved oxygen [8]. These FeSO melts can only exist under extremely non-canonical fO_2 values, eight to nine log units higher than solar, conditions which can only be achieved in transient plumes of gas generated during impacts between planetesimals [8]. In addition, the three-oxygen isotope systematics of SAMs point to a possible contribution of icy planetesimals to their formation.

Conclusions: Altogether, these observations point to the presence in the accretion disk of olivine-rich dust formed over ≈1.5 Myr and having been submitted to some alteration processes before its incorporation in chondrules. Collisions between early-formed first generation of planetesimals could be at the origin of this dust. Some chondrules obviously formed in impact-generated plumes.

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THE FORMATION ENVIRONMENT OF CHONDRULES AND CALCIUM ALUMINIUM RICH INCLUSIONS.
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Early solar system solids provide clues to the pre-planetary environment. The high abundance of chondrules in nearly all chondritic groups demonstrates that chondrule formation was a widespread process in the formation region of the small bodies that were parents to most meteorites. The process of chondrule formation likely triggered the accretion of asteroids [1]. On the other hand, the abundance of calcium-aluminium-rich inclusions (CAIs) is much lower and varies very widely between groups, from 3 % in CV and CO meteorites to less than 0.1% in ordinary chondrites and enstatite chondrites [2]. Hybrid CAI-chondrule objects are remarkably rare, even in CV3 and CO3 meteorites e.g. 3]. There is abundant evidence, most persuasively chondrule-matrix complementarity [4] suggesting that chondrules formed in a local environment to their accretion. In contrast, CAIs likely formed at a single and remote location [5] and must have been transported to the midplane at asteroidal distances. CAIs formed in a region that was highly reduced [e.g. 6] and with a relatively high irradiation flux [7], in addition to having formed in a region with much higher $^{26}Al/^{27}Al$. In this talk, I would like to compare and contrast the formation conditions of these early solids, present some new magnesium isotope data and explore what they are telling us about solar system formation.

Bulk chondrule magnesium isotope measurements by us and others (Fig. 1) show a distribution suggesting a range of initial $^{26}Al/^{27}Al$ values. These values reflect the bulk compositional isotope values that are not changed by closed system remelting, but isotope systematics may be later affected by open system influx or loss of material. We see some evidence that chondrules with lower model initial $^{26}Al/^{27}Al$ have a higher pyroxene/olivine ratio than ones with higher initial $^{26}Al/^{27}Al$, indicating that they have reacted with Si in a nebular gas [8], suggesting this gas-melt interaction has also affected Mg. These data suggests that chondrules were extensively affected by remelting in a high pressure environment. However there is little evidence that CAIs were affected by similar processes. While the presence of compound objects show CAIs were occasionally present in the CV chondrule forming region, the vast majority of CAIs do not show evidence for having experienced a high temperature flash heating event in the same nebular environment as chondrules formed, suggesting they typically were not present at the time and place of chondrule formation. Furthermore, many CAIs have fluffy delicate textures that would not survive flash heating processes intact. Some CAIs that we now observe in chondrites, and particularly unmelted CAIs, may have formed in a different location to chondrules and been added into the CV parent body *after* initial accretion of the body, either having formed late or being stored elsewhere first.

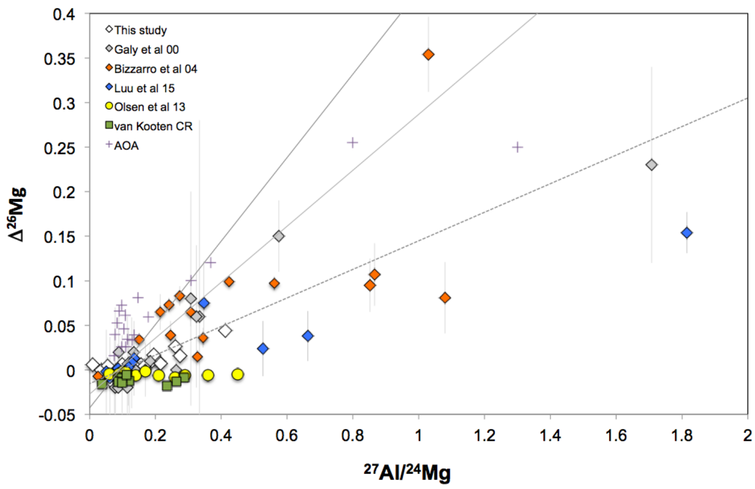

Figure 1: Bulk Mg isotope and Al/Mg data for chondrules from a study in preparation for publication [9] and from the literature.

References: [1] Alexander C. M. O'D et al. (2008) *Science* **320**, 1617-1619. [2] Hezel D. et al. (2008), *Meteorit. Planet. Sci*., **43** 1879–1894. [3] Russell et al. (2005) In "Chondrites and the Protoplanetary Disk" *Astron. Soc. Pacific Conf. Ser.* **341**, 317-350. [4] Palme H. et al., (2015) *Earth Plan. Sci. Lett*. **411** 11–19. [5] McKeegan K. et al. (1998) *Science* **280** 414-41. [6] Beckett J. and Grossman L., (1986) *LPSC* XVII, 36–37 [7] McKeegan K. et al. (2000) *Science* **289**, 1334–1337. [8] Libourel G. et al. (2006) *Earth Plan. Sci Conf.* **251**, 232-240 [9] Chen, H. Claydon, J., Elliott, et al. (2016) in prep for *Geochimica et Cosmochimica Acta.*

DUST GROWTH AND ITS EFFECTS ON TRANSPORT IN DISKS. F. J. Ciesla[1] and S. Krijt[2], [1]Department of the Geophysical Sciences, University of Chicago, 5734 South Ellis Avenue, Chicago IL 60637 USA.

Introduction: Protoplanetary disks are dynamic objects, through which mass and angular momentum are transported as part of the final stages of pre-main sequence evolution of the central star. Meteorites and cometary samples record a dynamic origin for our own solar nebula, as materials which formed in very different environments are found to be intimately mixed on the scale of centimeters. Understanding how protoplanetary disk dynamics give rise to the chemical mixing seen in Solar System objects is thus one of the key issues in studying the processes which shape the bulk properties of the planets. Further, understanding how materials are transported from the disk midplane (where planets form) to disk surfaces (which are probed by astronomical observations) is critical to interpreting astronomical analogs for our own solar nebula. Our recent work has focused on this issue.

Approach: Typically, material transport in protoplanetary disks is investigated by examining how a trace species is advected and diffused over the course of disk evolution (e.g. 1,2). More recently, a method for tracking the motions of individual grains in the disk to record the environments to which they were exposed has been developed, allowing the chemical evolution that arises as a result of particle transport to be investigated (e.g. 3-5) However, these approaches ignore the interactions of grains with other grains, which can lead to growth/fragmentation of those objects of interest. This, in turn, will affect the sizes of the species of interest and their resulting dynamical evolution in the disk. We have recently extended our particle tracking models to explore how materials are transported, accounting for the growth and fragmentation expected in a weakly turbulent protoplanetary disk. We have applied this to examine issues related to the transport of dust grains to the disk surface [6], the distribution of water and other volatiles in a protoplanetary disk [7,8].

Findings: Particle growth can significantly affect the ability of dust grains to be transported upward and outward in protoplanetary disks. While small dust grains are constantly resupplied in a disk via destructive collisions, the average monomer spends a large fraction of its time in larger aggregates, which preferentially stay around the disk midplane and drift inwards. I will discuss the broader implications of these findings for mixing in the solar nebula and interpretations of disk observations.

References: [1] Gail H.-P. (2004) *A&A 413,* 571-591. [2] Cuzzi J. N. et al. (2003) *Icarus, 166,* 385-402. [3] Ciesla F. J. (2010) *ApJ, 723,* 514-529. [4] Ciesla F. J. (2011) *ApJ*, *740,* #9. [5] Boss A. P. et al. (2012) *EPSL, 345,* 18-26. [6] Krijt S. and Ciesla F. J. (2016) *ApJ*, 822, #111. [7] Krijt et al. (2016) *ApJ*, In Press. [8] Ciesla F. J. and Krijt S. (2016) *ApJ*, Submitted.

FORMATION OF PLANETESIMALS. S. Ida[1], [1] Earth-Life Science Institute, Tokyo Institute of Technology, ida@elsi.jp

I will review the current theoretical models to form planetesimals. While small grains are coupled to the disk gas, larger particles drift inward, as a consequence of angular momentum loss by aerodynamical gas drag. For meter-sizes (assuming compact grains), the inward drift velocity is $\sim 10^{-2}$ au/yr [1, 2]. For small dust grains, growth via pairwise collisions is faster than drift so that they actually grow in situ until they reach 1-100 cm sizes (called "pebbles"). After that, the radial drift dominates [3, 4]. The drift timescale for pebbles is still much shorter than disk lifetime. If a solid (dust, pebble) layer can be geometrically thin and dense enough, planetesimals would form directly by gravitational instability in the dust disk before pebbles fall onto the star [5]. However, as a result of dust/pebble settling to the midplane, the vertical shear is generated between the solid sub-disk with Kepler rotation and the other gas-dominated region with sub-Kepler rotation, so that vertical Kelvin-Helmholtz instability would prevent the development of a thin and dense enough solid disk [6].

To overcome the drift barrier, "streaming instability" in the drifting pebble flow has been proposed [7, 8]. However, it has been recently recognized that a solid-to-gas ratio in the pebble migrating regions may be so low that the streaming instability is difficult to be established [9, 10]. Another possibility is pairwise collisions of fluffy grains [3, 11], although this can be applied to icy planetesimals but not to rocky planetesimals. Possibilities of formation at specific locations where pebble drift is
halted or slowed down are also discussed such as long-lived turbulent anti-clonic eddies [12, 13, 14, 15] or radial pressure bumps [16 and references therein].

Even without eddies or pressure bumps, the snow line could also be a special location of planetesimal formation by, for example, ice deposition beyond the snow line in turbulent disks [17, 18] or pile-up of small silicate cores ejected by sublimation of icy pebbles [19, 10]. In these cases, planetesimals are formed only near the snow line. However, since the snow line migrates according to disk evolution [20], planetesimals can be distributed in relatively broad regions.

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MODELS FOR CHONDRULE FORMATION IN THE EARLY SOLAR NEBULA. M.A. Morris[1], [1]State University of New York at Cortland, P.O. Box 2000, Cortland, NY 13045, melissa.morris@cortland.edu

Introduction: Chondrules are some of the oldest solids in the Solar System [e.g., 1], and are by far the most abundant, certainly some of the most studied, and quite possibly the least understood of early Solar System materials. The large range in formation ages of chondrules, from approximately 0-6 Myr after the oldest solids (calcium-rich, aluminum-rich inclusions, or CAIs) [1-5], and their ubiquity throughout the meteoritic record, make them ideal probes of the evolution of the early solar nebula, during the time "Before the Moon".

Constraints on Chondrule Formation Models: The formation mechanism of chondrules has been debated for decades, with various models falling in and out of favor. Any plausible model for chondrule formation must meet the numerous thermal, chemical, isotopic, physical, and age constraints recorded in asteroidal materials such as meteorites. The thermal histories recorded by chondrules have long been considered to be among the most important constraints on chondrule formation models. The most widely used method for determining the thermal histories of chondrules during crystallization has been via reproduction of natural textures using analog materials subjected to furnace experiments [see 6]. However, some of these results have recently been called into question [7-9].

Chondrule Formation Models: Numerous chondrule-forming mechanisms have been suggested to satisfy the constraints, including nebular shocks [e.g., 10-11], interaction of planetary bodies [e.g., 12], disk winds [13], lightning [e.g., 14], and magnetic current sheets [e.g., 15-16]. Nebular shock models can be broken down further into small-scale and large scale shocks, such as planetary bow shocks [e.g. 17] and those driven by gravitational disk instabilities [e.g., 18-19] or migrating massive planets [20]. However, it should be noted that very few chondrule formation models include additional predictions that can be tested further through examination of the meteoritic record, with the exception of the models of [e.g., 10-11; 21]. It should also be noted that some proposed chondrule formation mechanisms which had previously been ruled out (e.g., lightning), might need to be reconsidered if constraints on thermal histories are revised.

Discussion: Chondrule formation constitutes a major event (or events) in the early solar nebula, prior to and during accretion of planetary bodies, yet there are significant uncertainties in understanding this event(s). In this talk, I will provide a brief overview of various chondrule formation models, presenting my views on which meteoritic constraints they do or do not meet. I will also evaluate the possible need to revisit some of the meteoritic constraints, and whether it is correct to assume that all chondrules formed by a single mechanism, or whether we need to consider several different chondrule formation models.

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ACCRETION, MIXING AND DIFFERENTIATION OF PLANETARY BODIES. F. Nimmo[1], R. A. Fischer[1,2] ,N. Zube[1], S.A. Jacobson[3], D.P. O'Brien[4] [1]UCSC [2]Smithsonian [3]OCA Nice / BGI Bayreuth [4]PSI.

Introduction: The final stages of terrestrial planet accretion consisted of giant impacts between comparably-sized objects that had already differentiated [1]. Isotopic measurements provide constraints on the provenance of the materials from which the planets formed [2], and the timing of differentiation and mass delivery [3]. In particular, they may be able to test different hypothesized accretion scenarios, such as the Grand Tack [4]. Here I will focus on the Hf-W and Mo-Ru isotopic systems. The former provides an accretion chronometer, and the latter an indicator of provenance and mixing.

Hf-W system: An excess in mantle ^{182}W can be used to infer an equivalent core formation timescale [3]. In reality, core growth is discrete and stochastic; nonetheless, the Hf-W system can still demonstrate that e.g. Mars accreted an order of magnitude more rapidly than Earth [5]. The tungsten anomaly also depends on what fraction of an incoming core equilibrates with the target mantle (k), and what fraction of the mantle is involved (k'). Models assuming "canonical" accretion find that k~0.5 is required [6]. Conversely, for Grand Tack-style models [4], almost complete re-equilibration (k~1) is required (Figure 1). This is because the bulk of accretion is completed more rapidly in the Grand Tack paradigm, and is consistent with an independent constraint derived from partitioning of stable elements [7]. The fluid dynamics of mixing during giant impacts is poorly understood. Nevertheless, experiments suggest that k~1 only when impactors are small compared to the mantle depth [8], which is probably not true during the final stages of terrestrial planet accretion.

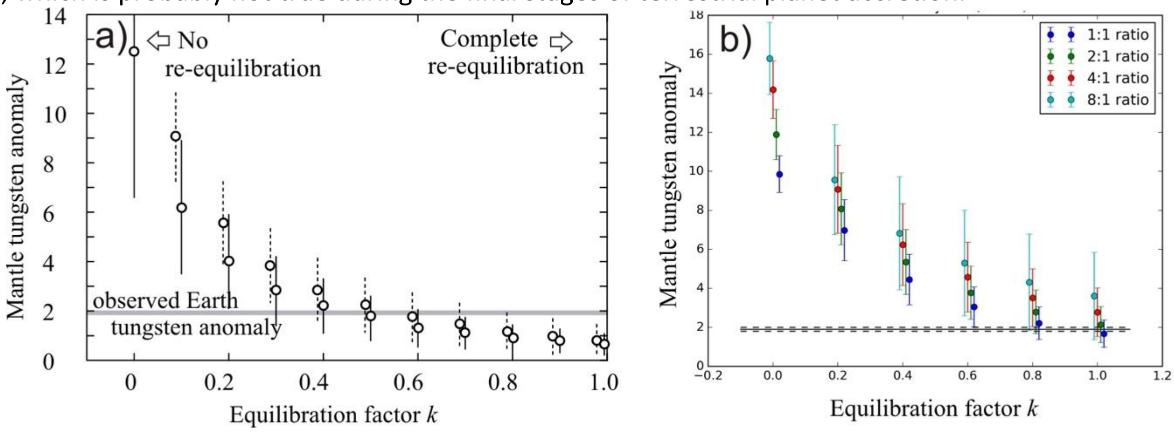

Figure 1. a) Mean model mantle tungsten anomaly for Earth-like bodies as a function of core equilibration factor k, in canonical accretion. Reproduced from [6]. b) As for a), but showing results from the Grand Tack scenarios of [4]. Colors indicate different ratios between the initial mass contained in embryos and in planetesimals.

Mo-Ru system: Different meteorite classes show a linear trend in Mo-Ru isotope space, with the Earth at one end [2]. Ru is usually considered to be siderophile (though this may not always be the case [9]), so that any Ru in the mantle must have been added after core formation was complete i.e. it forms part of the "late veneer". In contrast, Mo accumulates in the mantle throughout planetary growth. The Mo-Ru system can thus be used to test whether a planet has accreted from a well-mixed reservoir or not [2]. "Canonical" accretion simulations result in mixing in the inner solar system that is much less efficient compared to mixing in the Grand Tack scenario. In canonical scenarios, the reservoir has to be homogeneous out to 3.5-4 AU, while in the Grand Tack homogeneity is required out to 9-10 AU [10]. But the compositional variation of meteorites indicates that at least two reservoirs must be present in either case.

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THE COOL AND DISTANT FORMATION OF MARS. R. Brasser[1], S. J. Mojzsis[2], S. Matsumura[3] and S. Ida[1] [1]Earth Life Science Institute, Tokyo, Japan; [2]University of Colorado at Boulder, USA; [3]University of Dundee, UK

Introduction: With approximately 10% of Earth's mass, Mars is widely considered to be a stranded planetary embryo that never became a fully-grown planet[1]. A currently popular planet formation theory predicts that Mars formed near Earth and Venus and was subsequently scattered outwards to its present location[2]. In such a scenario, the compositions of planets are expected to be similar to each other[3]. However, bulk elemental and isotopic data for martian meteorites demonstrate that key aspects of Mars' composition are markedly different from that of Earth[4]. Geochemical data from martian meteorites suggests that the bulk composition of Mars is unlike that of the Earth (and Moon). Early investigations into Mars' bulk composition concluded that its primary constituents are a highly reduced component devoid of most volatiles, and more oxidised material containing CI abundances[5]; these are present in an approximately 2:1 ratio. These same studies concluded that Mars accreted homogenously, while Earth did not. Based on the analysis of the isotopic variations in O, Cr, Ti and Ni in various meteorites, terrestrial and martian rocks, this composition ratio was recently revised to Mars being a mixture of carbonaceous and non-carbonaceous material, with the former contributing only 9%[4]; for Earth the fraction is 24%. This conclusion is lent weight by several recent isotope studies in meteorites and in terrestrial and martian samples. The terrestrial isotopic composition of ^{17}O, ^{48}Ca, ^{50}Ti, ^{62}Ni and ^{92}Mo is best reproduced by a mixture of 90% enstatite chondrite, 7% ordinary chondrite and 2% carbonaceous chondrites[6]. In contrast, for Mars a mixture of 85% enstatite, 11% ordinary and 4% carbonaceous chondrites can match its ^{17}O, ^{50}Ti, ^{54}Cr, ^{62}Ni and ^{92}Mo values[7,8], which is different from Earth's and thus hints at a formation region well away from Earth's.

The combination of these results suggest that Mars formed outside of the terrestrial feeding zone. It is therefore probable that Mars always remained significantly farther from the Sun than Earth; its growth was stunted early and its mass remained relatively low[1]. Here we identify a potential dynamical pathway that forms Mars in the asteroid belt and keeps it outside of Earth's accretion zone while at the same time accounting for strict age and compositional constraints as well as mass differences. Our uncommon pathway is based on the Grand Tack[9] scenario of terrestrial planet formation, in which the radial migration by Jupiter gravitationally sculpts the planetesimal disc at Mars' current location. Our scenario suggests that Mars' volatile budget could be different from Earth's and predicts that Venus formed close enough to our planet that it is expected to have a similar composition.

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CR ISOTOPE SYSTEMATICS OF CHONDRULES. L. Qin[1,2], J. Liu[1], K. Zhu[1] and C. M. O'D. Alexander[2]. [1]CAS Key Laboratory of Crust-Mantle Materials and Environment, University of Science and Technology of China, 96 Jinzhai RD., Hefei, Anhui 230026, China; [2]State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing, China; [3]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA. (E-mail: lpqin@ustc.edu.cn)

Introduction: ^{54}Cr isotope anomalies are widely distributed in the Solar System [1,2]. At the bulk meteorite scale, it has been shown that different meteorite types have diagnostic ^{54}Cr anomalies, with C-chondrites show enrichments, E-chondrites show none, and O-chondrites and differentiated meteorites show depletions. This ^{54}Cr heterogeneity has been largely attributed to heterogeneous distribution of ^{54}Cr-rich nano supernova oxide particles identified in the matrix of C-chondrites [3, 4]. However the exact distribution mechanism of these particles among different meteorite classes are largely unknown. Chondrules represent coalesced dusk aggregates that experienced rapid melting and cooling. Chondrules are one of the oldest formed solids that record the formative stages of the Solar System, e.g. recent chronological studies suggest that formation of chondrules started as early as CAIs and expanded for a time interval of ~3 Myrs. Previous work showed that ^{54}Cr anomalies are variable among chondrules within some individual chondrites, but the cause is unknown [4]. The other benefit of studying Cr isotope systematics of chondrules is that ^{53}Mn-^{53}Cr is a short-lived chronometer, which could put chronological constraints on the formation of chondrules.

Methods: Individual chondrules were separated from chondrites using a freeze-and-thaw technique. The whole chondrule was dissolved and an aliquot of the sample solution was taken out and measured for major element concentrations and the Mn/Cr ratio. The rest of the sample solution was processed to extract Cr for isotopic analyses. The Cr isotopic analyese were performed on a Thermo Finnegan Triton plus TIMS at the University of Geosciences, Beijing, China. Both the chemical separation and mass spectrometry protols follow those described in [2]. The Cr isotope ratios are expressed in ε notation (relative deviation of the isotopic ratio in the sample from that in the standard times 10000).

Results: Chondrules from CR chondrite EET 92042 and CO chondrite Ornans were studied for Cr isotopic systematics. The $\varepsilon\,^{53}Cr$ values in both EET 92042 and Ornan are positively correlated with Mn/Cr and yielded initial $^{53}Mn/^{55}Mn$ ratios of $(4.7 \pm 1.2) \times 10^{-6}$ and $(7.2 \pm 1.6) \times 10^{-6}$, respectively. Using angrite D'Orbigny as an age anchor (initial $^{53}Mn/^{55}Mn = (3.23 \pm 0.04) \times 10^{-6}$[5]; Pb-Pb age = 4563.37 ± 0.25 Ma[6]), we obtain absolute ages of 4565.4 ± 1.4 and 4567.7 ± 1.3 Ma, respectively. Ornan chondrules demonstrated a large variation in $\varepsilon\,^{54}Cr$ from 0.2 to 1.1, while EET 92042 chondrules show a much smaller variation of ~1.2 to 1.6. $\varepsilon\,^{54}Cr$ and $\varepsilon\,^{53}Cr$ are postively correlated with each other for chondrules from the same sample, but with different slopes for the two chondrites. These results suggest: (1) chondrules from the same meteorite of EET 92042 or Ornans formed roughly at the same time; (2) chondrule formation ages are overlapping with the range of 0~3 Myr relative to CAI found by the previous work (e.g.[7]); (3) the heterogeneity in $\varepsilon\,^{54}Cr$ for chondrules from the same chondrite are results of volatility; (4) regardless of the diversity in the chemical composition, different chondrules and probably matrix from the same meteorite formed from the same reservoir and chondrules are formed locally; [5] preservation of ^{54}Cr-distinct reservoirs in the nebula for a period of a few million years.

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THE LINK BETWEEN CHONDRULE FORMATION AND CHONDRITE ACCRETION. C. M. O'D. Alexander, DTM, Carnegie Institution of Washington, 5241 Broad Branch Rd., Washington DC 20015, USA (calexander@carnegiescience.edu).

Introduction: The physical, chemical and textural properties of chondrules tend to be distinct between chondrite groups. In turbulent disks, chondrules would be transported over considerable distances on short timescales [1, 2]. Hence, the fact that chondrites have distinct chondrule populations suggests that chondrites must have formed relatively soon after most of the chondrules that they contain. The high densities required to prevent volatile loss and isotopic fractionation associated with evaporation in chondrules mean that chondrule forming regions could have been self-gravitating [3]. It has even been argued from petrologic observations that the OCs accreted while chondrules were still hot and plastic [4]. Finally, chondrules may be of an ideal size to enable planetesimal formation via the streaming instability [5] and/or turbulent concentration [2]. Thus, there are many reasons to think that chondrule and chondrite formation are linked.

Discussion: If most chondrules formed shortly before their parent bodies accreted, then most chondrules should have narrow age range that are similar to the estimated accretion ages of their parent bodies based on their group's thermal histories. Parent body processes can disturb chondrule ages, so it is essential to study only the most primitive chondrites and to select only those chondrules that can be shown to have undergone no secondary modification. The most careful ^{26}Al-^{26}Mg study of chondrule ages to date has been for the ungrouped CC Acfer 094 in which 9 of 10 chondrule ages are within error of a mean of 2.3 [illegible] Ma after CAIs [6]. Selecting only the same chondrule types as in the Acfer 094 work from a primitive CO [7] gives a mean age of 2.0 [illegible] Ma. Semarkona (LL3.0) chondrule ^{26}Al-^{26}Mg ages show more scatter, but have a mean of 2.0 [illegible] Ma [8, 9], which is consistent with an average ^{182}Hf-^{182}W age for H chondrite chondrules of 1.7±0.7 Ma [10]. Preliminary ^{26}Al-^{26}Mg data for three Kaba (CV3.1) chondrules give ages of 2-2.5 Ma [11], similar to the average ^{182}Hf-^{182}W age for Allende (CV3.6) chondrules of ~2 Ma [12]. Schrader, Nagashima [13] estimated an average age for 95% of CR chondrite chondrules of 3.7 [illegible] Ma, which is similar to a U isotope corrected bulk CR chondrule Pb-Pb age of 3.7 [illegible] Ma [13]. However, there are some CR chondrules without detectible ^{26}Mg excesses that may be significantly younger than these mean ages, prompting Schrader, Nagashima [13] to suggest a limit on the CR accretion age limit of >4.0 [illegible] Ma after CAIs.

Accretion ages have been estimated based on thermal modeling of peak temperatures and/or the formation/closure ages of secondary phases. Estimates for the accretion ages of the OCs are all ~2 Ma [10, 14-16]. The CO and CV chondrites seem to have formed at ~2.5 Ma [16, 17]. The carbonate ages in CIs, CMs, CRs and Tagish Lake are all similar and consistent with 3-4 Ma accretion ages [18, 19]. The organic matter in CRs suggests that they were the least heated of these CCs [20] and therefore probably formed last when ^{26}Al was barely able to melt accreted ice (i.e., ~4 Ma).

Conclusions: The accretion ages of chondrites are broadly consistent with the typical ages of their chondrules, but the current uncertainties do allow for time gaps of up to several hundred thousand years between the formation of most chondrules and their chondrite hosts.

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EVOLUTION OF PLANET-FORMING COMPONENTS IN THE FIRST MILLIONS OF YEARS OF SOLAR SYSTEM FORMATION. H. Yurimoto[1,2], [1]Hokkaido University, Sapporo 060-0810, Japan, [2]JAXA/ISAS, Sagamihara 252-5210, Japan (yuri@ep.sci.hokudai.ac.jp).

Hydrogen, nitrogen and oxygen are among the most abundant elements of the Universe. Isotopic compositions of these elements between molecules are highly variable in molecular clouds. Due to highly volatile nature of these elements, the chemical forms are easily changed between vapor and solid (ice) by environmental temperature and pressure. Thus, the standard planetary formation model of the solar system suggests that inner planets deplete these elements, but outer planets enrich as major elements. Isotopic compositions for planets of these three elements should be determined spontaneously according to the standard planetary formation processes. Therefore, the isotopic variation between planets would be an important key to clarify how to form planets in the solar system. In this report, we discuss evolution of planet-forming components in the first millions of years of solar system formation and infer isotopic compositions for H, N and O of planets.

We have proposed a model for oxygen isotopic evolution in proto-planetary disk [1], and inferred O isotopic compositions of outer planets [2]. The augmented model in these studies assume the initial condition of isotopic compositions of molecules observed in molecular clouds and in chondrites, and includes two key points, i.e., 1) temporal preservation of chemical species fractionated in mass and 2) astronomical space separation by dynamic coupling/decoupling due to the chemical form changes for H, N and O in the disk.

The model infers systematic increase of heavier isotope components of H, N and O for outer planets towards increasing redial distance from the sun, whereas relatively uniform isotopic composition for inner planets. Inferred H isotope variations between outer planets are quantitatively consistent with observation data by planet explorations [e.g. 3]. We infer enrichments of ^{15}N in the order of Jupiter, Saturn, and Uranus/Neptune. The $^{15}N/^{14}N$ ratio of Uranus/Neptune would be larger than the Earth's value. Oxygen isotope systematics between outer planets would be mass independent and ^{16}O component would be depleted in the order from Jupiter towards Neptune. The isotopic compositions of inner planets suggest significant accretions of ices from outer solar system during planetary growth and as late veneer.

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ESTABLISHING GENETICAL LINKS AMONG SOLAR SYSTEM MATERIALS USING NUCLEOSYNTHETIC RU AND MO ISOTOPE ANOMALIES. M. Fischer-Gödde[1], J. Render[1], C. Proksche[1] and T. Kleine[1]. [1]Institut für Planetologie, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany (m.fischer-goedde@uni-muenster.de).

Introduction: The isotopic composition of bulk meteorites is thought to reflect an integrated nucleosynthetic mixture of local presolar and nebular components incorporated into the parent bodies of meteorites at their formation region in the solar nebula. As a consequence, only materials with the same blend of nucleosynthetic components can derive from the same source reservoir. Thus, nucleosynthetic isotope anomalies represent a powerful tool to investigate genetic links among solar system materials.

The Cr and Ti isotopic compositions of meteorites showed the existence of a fundamental dichotomy between carbonaceous and non-carbonaceous meteorites [1], indicating that carbonaceous chondrites could have formed from an isotopically distinct solar system reservoir compared to the non-carbonaceous meteorites. If indeed carbonaceous chondrites derive from such a distinct reservoir, this should also be reflected by their Mo and Ru isotopic compositions. Mo and Ru are particularly useful to investigate this dichotomy because previous studies have shown that different meteorite groups display distinct nucleosynthetic isotope anomalies for these elements [2-5]. These studies also showed that most iron meteorites, enstatite and ordinary chondrites, and few carbonaceous chondrites display correlated Mo and Ru deficits as predicted from *s*-process nucleosynthetic theory [2,4,5]. Conversely, it was observed that some iron meteorite (IID, IVB) and carbonaceous chondrite groups do not plot on this correlation [5]. This suggests that a dichotomy could exist among meteorites, as found using Cr and Ti isotopes, but also that perhaps carbonaceous and non-carbonaceous meteorites could belong to both groups.

We addressed this issue using high-precision Mo and Ru isotope measurements by MC-ICPMS. We obtained Mo and Ru isotope data for a large set of bulk meteorites, including enstatite, ordinary, and carbonaceous chondrites, iron meteorites (IAB, IIAB, IID, IIE, IIIAB, IVA, IVB), as well as acid leachates and insoluble residues from Allende (CV3) and an enstatite chondrite (MIL 07028, EH3). All analyzed bulk meteorite groups display resolved Mo and Ru isotope anomalies. The isotopic compositions of most bulk meteorites show characteristic Mo and Ru isotope patterns indicative for a deficit in *s*-process nuclides. However, the vast majority of carbonaceous chondrites, the IID and IVB irons, and the Allende leachates display larger ε^{95}Mo and ε^{97}Mo and slightly smaller ε^{96}Ru and ε^{98}Ru anomalies, deviating from the *s*-process nucleosynthetic model and requiring the presence of an additional nucleosynthetic component. This is particularly clear in a plot of ε^{94}Mo vs. ε^{95}Mo, where the vast majority of carbonaceous chondrites and the Allende leachates together with the IID and IVB irons plot on a distinct *s*-mixing line than ordinary chondrites, IAB, IIAB, IIE, IIIAB and IVA iron meteorites, and the enstatite chondrite leachates. Hence, a dichotomy exists among meteorites, but not only between carbonaceous and non-carbonaceous material as suggested based on Cr and Ti isotope data. The distinction between these two groups may reflect the presence of SiC X grains in the carbonaceous meteorites and the precursors of the IID and IVB iron meteorites. These grains show characteristic excesses in ^{95}Mo and ^{97}Mo [6] and are thought to be produced during a supernova neutron burst [7]. Whether the SiC X grains derive from the same stellar source as the nucleosynthetic matter causing the disparate Cr and Ti isotopic signatures observed between carbonaceous and non-carbonaceous meteorites remains an open question.

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CONTROLS ON TERRESTRIAL PLANET COMPOSITION(S). R.W. Carlson, Carnegie Institution for Science, Department of Terrestrial Magnetism, 5241 Broad Branch Road, N.W., Washington, D.C., 20015, USA, rcarlson@carnegiescience.edu

Introduction: Traditional models used to estimate Earth's bulk composition [1-3] start with carbonaceous chondrites as these meteorites are closest to Solar in composition. Over the last decade, however, Earth has been shown to be distinct in isotopic composition compared to all groups of meteorites, except for enstatite chondrites, in a wide variety of elements (e.g. Ca, Cr, Ti, Ni, Zr, Mo, Ru, Nd, Sm) [4-6]. In these elements, the isotopic distinctions are nucleosynthetic in origin and reflect different mixtures of the elements provided by the stars that contributed to the Solar molecular cloud before its collapse to become the Solar System [7]. For some of these elements (e.g. Cr, Ti, Ni, Sm), Earth lies within the range defined by the different groups of meteorites and hence conceivably could reflect a mixture of the various groups [8]. For other elements (Mo, Ru, Nd), however, Earth lies at one end of the meteorite isotope arrays, indicating that no mixture of the existing meteorites provides a good isotopic match to Earth's composition [e.g. 9].

Another complication in the traditional models for estimating Earth's bulk composition is the realization that the main mass of Earth likely was not accumulated through the gentle accretion of primitive Solar System objects, but that planetesimal growth to planetary embryo size, perhaps even as large as Mars, occurred so quickly that global melting and differentiation of these objects was driven by ^{26}Al decay. Thus a large mass fraction of the building blocks of Earth could have been already differentiated planetesimals that had separated core from mantle, and outgassed their volatile constituents into an atmosphere that was subsequently gravitationally lost to space before they accumulated to what would become Earth. Given the dynamics of planet growth, collisions between differentiated planetesimals also is an effective way to separate metal for silicate (core from mantle) [10] and perhaps even incompatible lithophile element rich crust from mantle [11] should the collisions occur in a way that leads to preferential ejection of crust compared to mantle into the material that never reaccretes to the growing planet.

These factors complicate estimation of the bulk composition of planets as they introduce a number of mechanisms other than the nebular process of condensation as potentially important processes in controlling the composition of the final planet. Evidence from short-lived radiometric systems such as Mn-Cr [9] and Hf-W [e.g. 12] indicate that Earth's volatile depletion and metal-silicate separation occurred within the first few to tens of millions of years of Solar System evolution. These primary differentiation processes thus accompanied planet formation and were not the result of longer-acting processes, for example, plate tectonics and continent formation. Given the evidence that Moon formation may have occurred as late as 4.4 to 4.45 Ga [13], the difference in ^{53}Cr/^{52}Cr and ^{182}W/^{184}W ratios of Earth compared to chondrites suggests that the primary differentiation of Earth occurred before the giant impact that formed the Moon; and the evidence for that differentiation survived the giant impact.

Given the title of this meeting, another important observation is how quickly Earth's surface cooled and began the process of crust formation. A variety of data from the Hadean zircons of western Australia document the presence of water-saturated melting of rocks in the crust as early as 4.36 Ga [14]. If the 4.28 Ga age reported for the Nuvvuagittuq supracrustal rocks [15] dates their eruption, the presence of pillow basalts suggests their eruption into a body of water, either a lake or ocean, only some 100-150 Ma after the giant impact. The compositional stratigraphy of the Nuvvuagittuq rocks is similar to that displayed in some modern intraoceanic convergent margin volcanic settings [16], suggesting that something like plate tectonics had already begun on Earth by 4.28 Ga. Although the compositional consequences for Earth caused by the giant impact remain to be defined, the occurrence of both ^{182}W/^{184}W [17-19] and ^{129}I/^{130}I [20] ratio variability in Archean and even some Phanerozoic rocks suggests that the giant impact did not completely erase all features of Earth differentiation that predate the impact.

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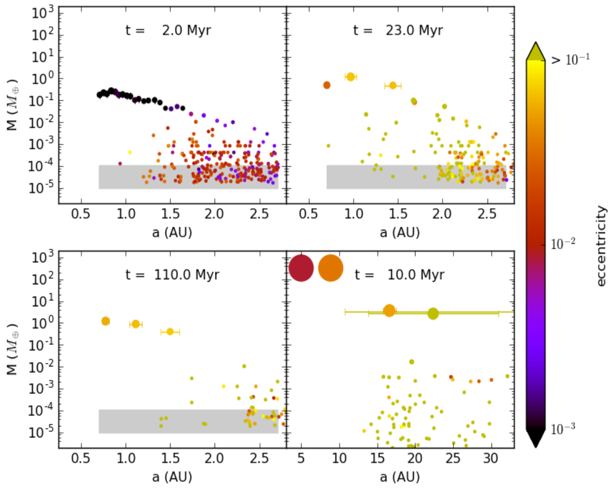
FORMING THE SOLAR SYSTEM FROM PEBBLES. K. A. Kretke[1] and H. F. Levison[2], [1]SSERVI (1050 Walnut Suite 300, Boulder, CO, USA, kretke@boulderswri.edu) , [2]Southwest Research Institute, Boulder (hal@boulder.swri.edu).

Introduction: In recent years, theories surrounding the formation of small-bodies and planets have been undergoing a radical shift. Particles with stopping times comparable to their orbital times, often called "pebbles" (although they range from sub-centimeter to meter sizes), interact with gaseous protoplanetary disks in very special ways. Gas drag can first concentrate the pebbles, allowing them to gravitationally collapse and directly produce the planetesimal building blocks, and then drag will cause them to be efficiently accreted on to these planetesimals, rapidly producing larger planetary embryos and even gas giant cores[1].



The evolution of a terrestrial planet system under pebble accretion. Panels (a) to (c) show the formation of a system of terrestrial planets. Each panel shows the mass of the planetesimals and planetary embryos as a function of semi-major axis, while color indicates their eccentricity. In addition, the `error bars', which are only shown for objects larger than 0.01 Earth masses, indicate the range of heliocentric distance that an object travels. The grey box shows the region populated by planetesimals at t=0. Panel (b) shows the distribution of planetary embryos after pebble accretion but before the dynamical instability. Panel (c) panel shows the final system. The panel (d) shows the fiducial giant planet system also formed by pebble accretion.

Methods: We use the planet formation code LIPAD (the Lagrangian Integrator for Planetary Accretion and Dynamics)[2] to model to collisional and dynamical evolution of a solar system forming under these conditions. LIPAD is based upson the N-Body integrator SWIFT [3] but uses novel aloritms to statistically follow bodies that are too small and numerous to be handled in a traditional N-body integrator. This allows us to model how our system may have evolved starting from pebbles and planetesimals all the way to a mature planetesary systems.

Results: We find that the pebble accretion model can succesfully explain many attributes of the Solar System: an outer Solar System with a few giant planets and ice giants and a out Kuiper belt [4], an inner Solar System with terrestrial planets, a small Mars, and a low mass asteroid belt [5]which consists of material mixed from the inner and outer Solar System.[6]

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THE EFFECTS OF DYNAMICAL EVOLUTION OF GIANT PLANETS ON THE ELEMENTAL ABUNDANCES OF TERRESTRIAL PLANETS. S Matsumura[1], R Brasser[2], and S Ida[2], [1] School of Engineering, Physics, and Mathematics, University of Dundee, DD1 4HN, Scotland; s.matsumura@dundee.ac.uk, [2]Earth-Life Science Institute, Tokyo Institute of Technology, Meguro-ku, Tokyo, 152-8550, Japan

Recent observations started revealing the diversity in compositions of protostellar disks and planets beyond the Solar System. With the expectation of the further constraints in the future, it is crucial to understand how the elemental compositions of planets are related to planet formation processes.

In this talk, we will take the Solar System as an example and discuss how the compositions of terrestrial planets are affected by the dynamical evolution of giant planets. To estimate the planetary compositions, we have followed previous studies and assumed that the initial compositions of the building blocks of planets could be approximated by a simple condensation model, and numerically studied the evolution of the compositions of planets as they were formed. To assess the dynamical effects of giant planets, we have considered a few different formation models of the Solar System. In this talk, we will focus on the classical planet formation model, where giant planets are on the current orbits, and the Grand Tack model, where Jupiter and Saturn first migrate inward and then outward.

We have found that the abundances of refractory and moderately volatile elements were nearly independent of formation models, and that all the models could reproduce the abundances of these elements of the Earth. The abundances of more volatile elements, on the other hand, depend on the scattering rate of icy planetesimals into the inner disk, as well as the mixing rate of the inner planetesimal disk. For the classical formation model, neither of these mechanisms are efficient and the accretion of more volatile elements during the final assembly of terrestrial planets appears to be difficult. For the Grand Tack model, both of these mechanisms are efficient, which leads to a relatively uniform accretion of more volatile elements in the inner disk. Our study shows that, in the limit of the simple condensation model, the compositions of terrestrial planets are better explained by the Grand Tack model than by the classical formation model.

The paper is available at http://iopscience.iop.org/article/10.3847/0004-637X/818/1/15/pdf or at https://arxiv.org/abs/1512.08182.

DISTRIBUTION OF HIGHLY SIDEROPHILE AND VOLATILE ELEMENTS IN PROTO-EARTH MATERIALS.

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The problem: A paradigm has arisen over the relationship of late accretion (often and probably incorrectly termed a late veneer, implying a gentle rain-down of impactors) and the delivery of water and other volatile compounds and elements (e.g., [1]). Late accretion, which can be defined as the addition of materials after metal-silicate equilibrium, is effectively tracked using the highly siderophile elements (HSE: Os, Ir, Ru, Rh, Pt, Pd, Re, Au). Thus, there should be a link between the HSE and volatile elements. Alternatively, the distribution of volatile elements and the HSE in the Earth and Moon were set by a range of fundamental processes, including planetary accretion processes and the feedstocks that formed the proto-Earth and Moon, as well as late accretion. The timing of these processes on planetary bodies likely varied in response to mechanisms of accretion, availability and nature of feedstock materials, and cessation of metal-silicate equilibrium. Arguably, the most complex locations to address these issues in the inner Solar System are the Earth and Moon. The likely origin of these bodies, during a late-stage catastrophic 'Giant Impact', led to significant volatile loss from the Moon, redistribution of the HSE and volatile elements between the colliding bodies, planetary-scale magma oceans, prolonged late accretion and, in the case of Earth, silicate remixing (aka Plate Tectonics). Given this diverse array of processes, how is it possible to go about deriving likely distributions of the HSE and volatile elements in Proto-Earth or Moon materials?

Possible solutions?: Current estimates of the addition of late accretion materials to Earth and Moon from the HSE imply between 0.5-0.8% of the mass of Earth was added by late accretion (e.g., [2]), whereas some 20-40 times less proportional amount of mass is estimated for the Moon [3]. In contrast, to explain the amount of moderately volatile elements - including Pb and Zn - present in the mantle of Earth requires much higher proportional mass addition (~5-12% [4,5]). Various models have been used to explain this difference, including physical mechanisms, such as partial vaporization of massive impactors [6], leading to a physical process of separation of elements according to phases that they concentrate into. For example, partial vapourisation of a large impactor would lead to all of the lithophile and volatile elements being retained in the silicate mantle or resulting vapour cloud. In contrast, the HSE and Fe would mostly pool and sequester into Earth's core, with some fraction of the HSE also being retained in the vapour cloud that would subsequently rain down on the Earth's surface, imparting a 'late accretion' signature. A model of volatile element loss during giant impact, followed by stochastic late-accretion of volatiles to Earth and the Moon has significant deficiencies, however. It is not clear how reasonable 5->10% late accretion for Pb and volatile elements is after Giant Impact, given that the Earth-Moon forming event is widely considered the last major accretion event (e.g., [7]). Nor is it known if the giant impact was a global 'clearing house' event for the HSE in Earth. Understanding if both the Earth and Moon were systematically depleted in volatile and HSE during their formation is a crucial constraint for assessing whether a late-accretion model for volatile enrichment can work. Scenarios that use a high ice/rock ratio (e.g., comets) could help to reduce the mass balance problem, but cometary material does not seem consistent with volatile element isotopic data (e.g., [8]).

Given the discussion above, a giant impact and/or late accretion scenario to explain moderately volatile element distributions in Earth and the Moon remains unconstrained, and alternative explanations need to be sought. I will review evidence from the distribution of volatiles and HSE in chondrites and achondrites – the likeliest examples of possible feedstock materials to the proto-Earth and Moon and possible scenarios of feedstock composition derived from volatile, HSE and lithophile isotope systematics.

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ENSTATITE CHONDRITES, THE EARTH-LIKE RESERVOIR AND THE TIMING OF GAP OPENING IN THE EARLY SOLAR NEBULA BY JUPITER FORMATION. Q.-Z. Yin[1], E. Gaidos[2], M. E. Sanborn[1], and Shijie Li[3]. [1]Dept. Earth & Planet. Sci, Univ. of California, Davis, CA 95616, (qyin@ucdavis.edu), [2]Dept. Geol. & Geophys., Univ. of Hawai'i at Manoa, Honolulu, HI 96822. [3]Institute of Geochemistry, CAS, Guiyang, China.

We report the ^{53}Mn-^{53}Cr age of chondrules extracted from the most primitive EH3-type enstatite chondrite, *Qingzhen*, one of the most reduced meteorites, well known for its Si-bearing metal, and sulfide phases that contain typically lithophile elements. The ^{53}Mn-^{53}Cr isochron obtained for Qingzhen gives an initial $^{53}Mn/^{55}Mn$ of $(3.69\pm1.08)\times10^{-6}$ and $^{53}Cr_i$ = -0.11±0.08 (MSWD = 0.44). Relative to the D'Orbigny age anchor with its U isotope-corrected Pb-Pb age ([1]Amelin, 2008; [2]Brennecka and Wadhwa, 2012) and its precise $^{53}Mn/^{55}Mn$ ([3]Glavin et al., 2004; [4]Yin et al., 2009), we obtain a 4,564.8±1.6 Ma formation age of Qingzhen's chondrules.

Unlike Allende (CV3) chondrules ([4]Yin et al., 2009), the ^{54}Cr anomaly of each individual chondrule in Qingzhen is uniform and Earth-like (with an average ^{54}Cr = 0.12±0.14). Enstatite chondrites (ECs) and enstatite achondrites (aubrites) are remarkable in their isotopic similarity, as well as their chemical dissimilarity to Earth (*c.f.* [5]Gaidos and Yin 2015). We argue that our Qingzhen chondrule ^{53}Mn-^{53}Cr age dates the Earth-like pre-planetary reservoir formation/isolation in the solar nebula, which is distinct isotopically from most materials in the inner Solar System. Isotopic homogeneity of this reservoir is clearly established at both micro- and macroscopic levels by 4,564.8±1.6 Ma. Because our ^{53}Mn-^{53}Cr age and a few other established sulfide ages of ECs and aubrites ([6]Wadhwa et al., 1997; [7]Guan et al., 2007; [8]Telus et al., 2012) all precede the Moon-forming giant impact ([9]Yin et al., 2002; [10]Kleine et al., 2009) and the fact that post-impact Earth and the Moon are isotopically very similar to ECs and aubrites, the impactor *Theia* must also have been isotopically very similar to ECs and Earth. Otherwise, the post-giant impact Earth and the Moon would deviate isotopically from that of ECs. Likewise, the isotopic similarity of Earth and ECs and the Earth's unique end-member position in multi isotopic space constrains the amount of any non-enstatite-like material accreted either before or after core closure ([11]Dauphas et al., 2004; [12]Fischer-Goeddle et al., 2015).

We infer that the closure of the Earth/EC-like isotopic reservoir by 4,564.8±1.6 Ma represents the formation of Jupiter and the clearing of the disk immediately outside the terrestrial planet formation zone, as well as excitation of planetesimals. This is consistent with the latest observations and models. We suggest that the EC reservoir deviated at 4,564.8±1.6 Ma, or shortly thereafter, from that of the Earth's chemically, by SiO/SiS gas interactions with solids ([13]Lehner et al., 2015), creating its unique chemistry, explaining its low ^{30}Si and low Mg/Si ratio ([14]Dauphas et al., 2015). The processes responsible for changes in EC chemistry must be a local phenomena, as it did not affect the bigger reservoir represented by the bulk Earth composition. Existing ^{53}Mn-^{53}Cr dates on sulphide phases in ECs (e.g. [8]Telus et al., 2012) tend to be much later than 4,564.8±1.6 Ma. However, the ^{53}Mn-^{53}Cr systematics in sulphides could be affected by parent body processes, whereas SiO/SiS gas interaction with solids which changed the EC chemistry could not have occurred on a parent body.

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MAGMA OCEANS IN THE EARTH-MOON SYSTEM. M. Boyet[1], R.W. Carlson[2], [1]Laboratoire Magmas et Volcans CNRS, Université Blaise Pascal, 6 avenue Blaise Pascal, 6318 Aubière Cedex, France; M. Boyet@univ-bpclermont.fr, [2]Carnegie Institution for Science, Department of Terrestrial Magnetism, 5241 Broad Branch Road, N.W., Washington, D.C., 20015, USA; rcarlson@carnegiescience.edu

Introduction: The formation of the Moon by a large collision between a planetary body and the proto-Earth in the last stages of terrestrial accretion explained most of the Earth-Moon system characteristics. Although this mode of formation for the Earth's satellite has received unanimous support, the scenario of the collision is still controversial. Contrary to the canonical giant-impact model suggesting a Mars-sized body impactor [1], the last proposed dynamical simulations [2-4] are all able to explain the Earth-Moon isotope similiarity (O, Si, Ti, etc [5-7]). However these simulations involve various initial conditions (e.g. size of the impactor, impact velocity, etc) that could lead to different consequences of the impact for Earth in terms of the degree to which the impact erases all evidence of prior differentiation events on Earth. Here we will review the isotope results obtained on lunar and terrestrial samples with the aim to answer to the following questions: 1) When did the giant impact occur? 2) Did the giant Moon forming impact induce complete homogenization of the mantle?

A young age of Moon formation: The different approaches that have been used to date the giant impact have resulted in ages that vary from 50 Ma to 250 Ma after the beginning of Solar System accretion, but the majority of estimates range between 150 and 200 Ma. All of them consider the same evolution. Mafic silicates crystallized from an initially extensively molten Moon and subsequently sank into the lunar mantle to form the source regions of much later mare basalt magmatism [8]. After some 70-80% crystallization, plagioclase began to crystallize from what was by then a dense iron-rich differentiated magma, causing the plagioclase to float to form the ferroan anorthosite suite (FAS) of the lunar highlands rocks. Further crystallization resulted in a residual liquid strongly enriched in incompatible elements that was given the name KREEP, based on its marked enrichment in K, REE and P, among many other incompatible elements.

Absolute ages have been determined on FAS rocks (internal isochrons, zircons) from multiple isotope dating techniques. All other estimates are model ages for lunar magma ocean crystallization obtained from the measurements of lunar basalts and samples from the Mg-suite lunar crustal rocks. All these ages cluster between 130 and 200 Ma after the beginning of Solar System accretion. The lunar formation ages approach the oldest age of 4374 ± 6 determined on Jack Hills zircon (SW Australia) [9]. This terrestrial age provides the most robust young age limit for the giant impact forming the Moon. Many interpretations have been presented concerning the ages obtained on lunar samples. For example, how well do the ages of FAS rocks or those of lunar zircons approximate the time of crystallization of the magma ocean?

An old age of Moon formation: Three papers with different approaches (I-Pu-Xe, ^{146}Sm-^{142}Nd and HSE modeling) have proposed ages that are significantly older, between 40 to 100 Ma for the formation of the Moon [10-12]. Several short-lived isotope systematics measured on terrestrial samples also suggest that Earth recorded a global differentiation event linked to the crystallization of a magma ocean, core formation and mantle outgassing in the first 100 Ma [13-15]. A young age for the formation of the Moon seems to contradict several isotope signatures (W and Xe) measured on terrestrial samples, but could be reconciled if the giant impact did not cause complete melting and homogenization of the Earth's mantle, or significant reequilibration of core and mantle. This would imply the preservation of reservoirs in the deepest part of the Earth's mantle of chemically distinct material formed before the giant impact. The extent of mantle melting has been tested numerically for the different impact scenarios [16]. The results show that the canonical model allows the preservation of mantle heterogeneities whereas for other models, complete mixing is more probable.

Successive magma ocean events: Geochemical evidence for the existence of magma oceans exists for small planetary bodies and planets. Rapidly after the beginning of Solar System accretion, the melting is induced by the presence of short-lived radionuclides such as ^{26}Al, whereas after a few

Ma, both the gravitational energy liberated by accretion and core segregation will enhance significantly the temperature. For the Earth, the existence of two successive magma ocean stages has been proposed from the study of several isotope tracers: i) the high $^{3}He/^{22}Ne$ fractionation observed in the Earth's mantle [17]; and 2) the ^{142}Nd difference of 20 ppm measured between chondrites and modern terrestrial samples [18]. Recent investigations of primitive Solar System materials have clearly shown that the ^{142}Nd isotope was heterogeneously distributed in the Solar System during accretion questioning an early Sm/Nd fractionation event for the Earth [19-20].

Successive collisions have been evoked for explaining the Martian hemispheric dichotomy [21], and the dichotomy between the two lunar hemispheres [22]. The time intervals between the crystallization of the magma ocean and the second impact are comprised between a few tens of Ma to 100 Ma. Initial ^{142}Nd data for FAS [11] suggest that not all FAN derive from the same source magma, as would be expected if they crystallized from a single magma ocean. Two successive melting events on the Moon need to be further investigated in order to explain the lunar chronology.

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WHAT DO WE REALLY KNOW ABOUT MAGMA OCEAN OXYGEN FUGACITY? J. W. Hernlund[1], S. Labrosse[2], H. Ichikawa[3], G. Helffrich[1], K. Hirose[1], [1]Earth-Life Science Institute, Tokyo Institute of Technology, 2-12-1-I7E-311 Ookayama, Meguro, Tokyo 152-8550, Japan, [2]Ecole Normale Superieure de Lyon, 46 Allée d'Italie, 69364 Lyon Cedex 07, France, [3]Earth-Life Science Institute, Ehime University, 2-5 Bunkyōchō, Matsuyama-shi, Ehime-ken 790-0826, Japan.

Introduction: In the past decade there have been numerous ideas advanced regarding magma oceans and core formation. One of the most prominent ideas invokes a variation in the redox state of a magma ocean during accretion, beginning with relatively reducing conditions in order to reconcile moderately siderophile element (MSE) abundances in the mantle with experimental melt/solid partition of MSEs (particularly Ni and Co). This idea, which is rooted in an attempt to allow core formation at mantle melting temperatures, has been expanded considerably since it was introduced by Wade & Wood [1]. Attempts to justify this scenario based on disproportionation of ferrous into ferric and metallic iron (i.e., $3Fe^{2+}$->$2Fe^{3+}$+Fe^{0}), driven by the strength of a coupled Al^{3+}-Fe^{3+} substitution in the mineral bridgmanite [2], have been advanced [3-4]. An increase in oxygen fugacity has also been proposed to arise by early accretion of material predominantly from the innermost solar system, following by later accretion of more oxidized material further outward [5]. Accretion and core formation models employing the Grand Tack scenario have been used to investigate and integrate this scenario into a large model space. Clearly, a considerable body of contingent work has been built on the assumption of evolving magma ocean oxygen fugacity during core formation. What if this idea is completely wrong?

Recently, the idea of core formation under reducing conditions has been under attack from a variety of angles. Siebert et al. [6] used partitioning constraints including V and Cr to argue that core formation must have taken place at conditions significantly more oxidizing. This argument was recently expanded to include comparisons with seismological constraints [7]. Arguments have also recently appeared to support the idea that at least some core formation took place at temperatures considerably higher than the mantle melting temperature, in order to allow for ingestion of enough MgO into the core to drive the early geodynamo by buoyant exsolution/expulsion of Mg-bearing compounds [8-9].

Here we will present further arguments based on simple energy conservation principles to show that the temperatures of magma oceans, particularly during metal-silicate equilibration, could have been maintained at temperatures up to 1,000 K higher than the silicate liquidus. We will show that the common idea that metal-silicate equilibration takes place at the bottom of a magma ocean, at temperatures near the silicate liquidus, is likely to be wrong. Furthermore, we will show how a new experimental discovery at ELSI [10] can directly constrain the range of plausible oxygen fugacities during core formation. The preferred model we arrive at for metal-silicate equilibration in a magma ocean is very similar to a high temperature scenario that was discussed and subsequently rejected as being "physically implausible" by Wade and Wood [1]. Their rejection of this high temperature scenario is precisely what motivated their proposal for evolution of oxygen fugacity.

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EVOLVED CRUSTS IN DYNAMICALLY 'HOT' PLANETARY EMBRYOS. S.J. Mojzsis*[1], J.J. Oulton*[1], A. Bischoff[2], R. Brasser*[3] *Collaborative for Research in Origins (CRiO); [1]Department of Geological Sciences, University of Colorado, Boulder, Colorado 80309-0399 USA (mojzsis@colorado.edu); [3]Institute for Planetology, Westfälische Wilhelms Universität, Münster 48149 Münster, Germany; [3]Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo 152-8550, Japan.

Introduction: Earth sustains crustal recycling driven by plate tectonics in a watery setting that produces abundant granitic melts, and ultimately, continents [1]. Evidence from the oldest terrestrial zircons shows that this process was underway within the first ~190 Myr of our planet's history [2]. Production of petrologically intermediate to evolved rocks of the andesite-granitoid-granite suite, however, is not unique to Earth. Granitoid (granodiororite) and various intermediate felsic rocks of unconstrained ages are documented on Mars [3], lunar granophyres and other felsites have long been known [4], and broadly "felsic" poly-mineralic rock fragments akin to granophyres are found in some asteroidal meteorites [5-10]. We report new petrologic and geochemical data to show how the oldest of these meteoritic granitoid assemblages yield information on an hitherto unquantified dynamically "hot" population of large (>>50 km), differentiated planetary embryos which were disrupted in the epoch of planetary mergers during the first ca. 10-50 Myr of the solar system [11,12].

Felsic melts in the early solar system: "Granitic" fragments in the *Adzhi-Bogdo* LL3-6 chondrite breccia represent highly fractionated melt production on an extinct(?) parent body ca. 40 Myr after CAIs. Another such fragment was recently reported from the polymict ureilite *EET87720* [13]. Previous exploratory ion microprobe U-Pb geochronology on a single ~15 μm zircon grain from an *Adzhi-Bogdo* clast gave an imprecise age of 4.6 ± 0.2 Ga [14]. Further Pb-Pb measurements on phosphates and other co-genetic phases yielded a Pb-Pb isochron age of 4.48 ± 0.12 Ga (2σ), and a (re-calculated) weighted mean age of 4.533 ± 0.04 Ga (2σ; mswd=0.6), respectively [5]. These ages for *Adzhi-Bogdo* could represent either (i) crystallization of the parent magma well before even the oldest lunar granophyre zircons at ca. 4.417 Ga [15], or (ii) reset ages [16,17]. Similar ca. 4.53 Ga ages have been ascribed either to an igneous- or impact-related origin for the HED parent body [16, cf. 18].

Nature of the oldest felsic rocks: Known clast-hosted phases in *Adzhi-Bogdo* include: albite, orthoclase, quartz/tridymite, ilmenite, apatite, pyroxene, whitlockite/merrillite, (rare) zircon, and aenigmatite (Na, Ti, Fe-silicate). Preliminary oxygen isotope analyses on the granitoid clasts showed positive $\Delta^{17}O$ values super-parallel to the TFL and similar to that of the ordinary chondrites [19], and CR [20]. Here, we present new geochemical and petrologic data from *Adzhi-Bogdo* to answer the following questions: Were the solidification temperatures of these melts relatively cool, indicative a hydrous melt? Or did these clasts crystallize at higher temperatures in the absence of water (e.g. in an impact-generated magma ocean)? Was the parent body of the *Adzhi-Bogdo* "granitoids" differentiated? Did it have a dynamo? Do the reported ages reflect crust formation events, or re-setting from a dynamically excited impact bombardment regime [12]? What constraints can be made on the number and size planetary embryos that gave rise to granitic crusts before the Moon?

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OXYGEN ISOTOPES ON AN OLD MOON. K. D. McKeegan, Dept. of Earth, Planetary, and Space Sceinces, University of California - Los Angeles, Los Angeles, CA. 90095, USA. (mckeegan@epss.ucla.edu).

Introduction: Oxygen is the most abundant element in the solar system between the orbits of Mercury and Jupiter. In the solar nebula, oxygen isotopes were fractionated in a non-mass-dependent sense between various chemical reservoirs, by as yet unknown processes, such that oxygen isotopic "anomalies" are heterogeneously distributed on all spatial scales in meteoritic components. The magnitude of the fractionation(s) that are partially preserved in small components of unequilibrated meteorites is up to ~250‰ [1,2]. This range appears to be highly contracted, to about 10-15‰, among asteroidal-sized bodies and is limited to < 0.5‰ among bodies large enough to have undergone metal-silicate differentiation [3]. Recent ultra-high precision data by Young and colleagues [4] show that the Earth and Moon share the same oxygen isotope composition to within 5ppm, exaccerbating the "isotope crisis" for giant impact models of the Moon's formation and tightening constraints on post-impact mixing processes and/or the accretion histories of the colliding objects. However, modelling the accretional histories (compositions over time) of objects comprising the inner solar system is challenging [4,5] in part because there are few data to constrain the initial $\Delta^{17}O$ distribution in the solar nebula (aside from the composition of the Sun, [6]). Chronology can also play a role in constraining impact scenarios by delimiting how much time is available for isotopic evolution of inner solar system bodies and what population of potential impactors exists at a given time. In the context of this workshop, the chronology question can be phrased "how much time is there *Before the Moon*?"

Dating the Moon: The age of the Moon is controversial, with some researchers arguing for a relatively late formation approximately 150 to 200 million years after the beginning of the solar system based on Sm-Nd ages of some ferroan anorthosites thought to be early flotation cummulates of the lunar magma ocean [7,8]. I will discuss new U-Pb and Hf isotope data (Fig. 1) obtained at UCLA and Princeton that demonstrate that some lunar zircon grains crystallized with very low initial $^{176}Hf/^{177}Hf$ ratios (near the solar system initial value), implying early chemical differentiation of the lunar crust. The zircon data require formation of the Moon within the first ~60 million years of the solar system. A giant impact in this shorter time frame is more readily accommodated by most dynamical models.

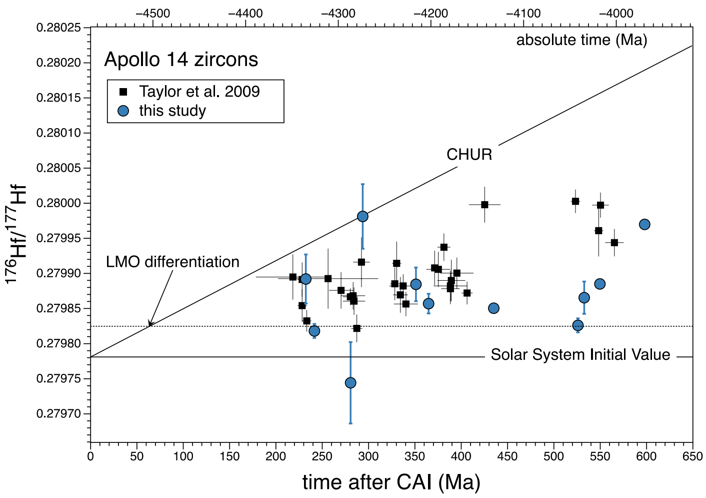

Fig. 1. Initial $^{176}Hf/^{177}Hf$ measured in individual Apollo 14 zircons as a function of U-Pb crystallization age. The Hf isotope data are corrected for exposure to cosmic radiation and the CHUR parameters are from [9]. A miniumum age for differentiation of the lunar crust is derived from the intercept of the least radiogenic Hf in zircons with CHUR. Data from Barboni et al. [10] and Taylor et al. [11].

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