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Comparative planetary mineralogy: V systematics in planetary pyroxenes and fO_2 estimates for basalts from Vesta. J.M. Karner¹, J.J. Papike¹, and C.K. Shearer¹. ¹Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87112.

Introduction: As part of the Lunar and Planetary Institute's "Oxygen in the Solar System" initiative, we have been developing V valence oxybarometers (VVOs), as measured in basaltic phases. Vanadium can exist as V^{2+} , V^{3+} , V^{4+} , and V^{5+} , and thus VVOs record at least 8 orders of magnitude of fO_2 , and are especially applicable to reduced planetary materials. Our first V work concentrated on basaltic glasses [1, 2], but now we are developing VVOs for chromite [3, 4], olivine [5] and pyroxene [6]. A VVO for pyroxene will be particularly useful for the study of basalts from asteroids (i.e. eucrites), and from Mars, in which pyroxene is an early crystallizing phase. This study explores the behavior of V in pyroxenes from planetary basalts and estimates the fO_2 of basalts from 4 Vesta.

Comparative planetary mineralogy-pyroxene:

The samples we studied are basalts containing pyroxene from the Earth, Moon, Mars and Vesta. The terrestrial sample is a Hawaiian basalt, while the lunar sample, 12075, is an Olivine basalt from the Apollo collections. The martian samples are DaG 476 and Shergotty, both basaltic shergottites. Pasamonte is an unequilibrated eucrite basalt presumed to be from Vesta. Pyroxene grains from each sample were analyzed by EMP to determine their major element compositions and then by SIMS to determine V concentrations.

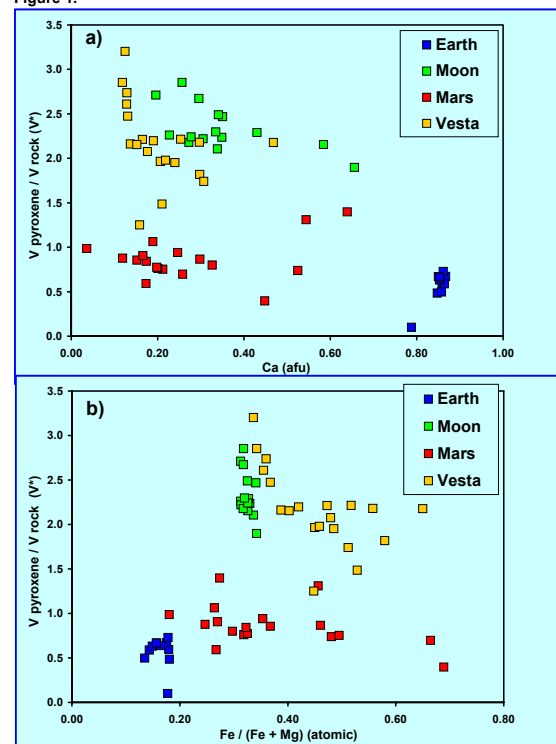
V systematics in pyroxene: Figure 1a, b plots Ca and Fe# content in pyroxene grains versus V pyroxene / V rock. Here we use the measured V in pyroxene and normalize to literature values of V in the rock, and call this value V^* . V^* is not a true D -value because some of these basalts are not melts but cumulates, and thus V^* does not represent the equilibrium distribution of V between pyroxene and the coexisting melt. The plots show that V^* values are lowest in terrestrial pyroxene, slightly higher in martian pyroxene, and much higher and comparably equal in pyroxene grains from the Moon and Vesta. The figure also shows that V partitioning appears to be little affected by either Ca content or Fe# of the pyroxene, except perhaps slightly in the lunar and Vesta case. We believe the most controlling factor on V partitioning in pyroxene is the variable fO_2 conditions of the planets. At relatively high fO_2 conditions, such as on Earth and Mars (~IW+1 to IW+4), low V^{3+}/V^{4+} in basaltic melts results in low V^* values because V^{4+} is slightly incompatible in pyroxene from Earth and more compatible for Mars. Conversely, low fO_2 conditions on the Moon and

Vesta lead to high V^{3+}/V^{4+} in melts, and subsequently high V^* values because V^{3+} is quite compatible in pyroxene. Furthermore, the slight decrease in V^* with crystallization in both lunar and Vesta pyroxenes is the behavior one would expect for a highly compatible element. Lastly, these systematics demonstrate that the charge-balance couple $^{M1}V^{3+} - ^{IV}Al$ is much more compatible in the pyroxene crystal structure than $^{M1}V^{4+} - 2^{IV}Al$ [6].

fO_2 estimates for basalts from Vesta: V systematics show that eucrite pyroxene grains crystallized from melts with high V^{3+}/V^{4+} , and thus low fO_2 conditions, and that lunar pyroxenes experienced similar histories. Our VVO for glass [1, 2] shows that basaltic melts are dominated by V^{3+} at fO_2 conditions below IW+1, and that lunar basalts crystallized at IW-1 to IW-1.7. Based on these arguments we believe eucrites crystallized at similar fO_2 conditions. Our results are in agreement with recent estimates [7] of IW-1 for basalts from both the Moon and Vesta.

References: [1] Sutton et al. (2005) *GCA*, in press. [2] Karner et al. (2005) *Am-Min*, in review. [3] Papike et al. (2004) *Am-Min*, 89, 1557. [4] Righter et al. (2005) *LPS XXXVI*, Abstract #1140. [5] Sutton and Newville (2005) *LPS XXXVI*, Abstract #2133. [6] Papike et al. (2005) *Am-Min* 90, 277. [7] Jones (2004) *LPS XXXV* Abstract #1264.

Figure 1.



OXYGEN FUGACITY VARIATIONS WITHIN AND AMONG METEORITE PARENT BODIES. Dante S. Lauretta, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85745. lauretta@lpl.arizona.edu

Introduction: Meteorites consist essentially of the silicate minerals olivine and pyroxene, iron-nickel alloys, sulfide minerals, and an enormous variety of accessory minerals. Most meteorites originate from the asteroid belt. The geologic diversity of asteroids and other rocky bodies of the solar system are displayed in the enormous variety of textures and mineralogies observed in meteorites.

Different classes of chondritic meteorites are discernable by their bulk chemistry, mainly the oxidation state and distribution of iron. Chondritic meteorite classes are subdivided by petrologic type. These designations reflect the extent to which these materials were altered by parent-body processes. Type-3 chondrites are the most primitive and have experienced minimal alteration. Silicate compositions in type-3 chondrites span a wide range of Fe-contents, reflecting a wide range of oxidation states for the formation of their varied components.

Type-1 and type-2 chondrites have experienced aqueous alteration while types 4-6 have experienced varying degrees of thermal metamorphism. Thermal metamorphism results in significant changes to meteorite textures and mineralogy. In particular, the compositions of silicate minerals become increasingly homogenous throughout the sample. Because of their varied oxidation states, silicate compositions in equilibrated chondrites vary among the different classes.

Oxygen Fugacity – An Introduction:

In many gaseous systems it is appropriate to assume that gases follow an ideal equation of state, known as the ideal gas law:

$$P \cdot V = n \cdot R \cdot T$$

P = pressure, V = volume, n = the number of moles, R is the gas constant, $82.06 \text{ cm}^3 \text{ atm mol}^{-1} \text{ K}^{-1}$, and T = temperature. However, in many systems, interactions among gas molecules result in deviations from ideality. Thus, it is often necessary to apply a correction to adjust for non-ideal behavior. A common way to correct for the effects of non-ideality is replace the pressure (P) with fugacity (f). The fugacity of a gas is related to the pressure through:

$$f_i = \gamma_i \cdot P_i$$

γ_i is the fugacity coefficient and P_i is the partial pressure of component i in the gas. For an ideal gas, $\gamma_i = 1$.

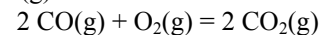
Whenever dealing with the chemical potential of a component in a gas phase, or a component that may be in a gas phase, fugacity can be used to account for the variation in the chemical potential of interest. More

precisely, since chemical potential is a quantitative measure of the reactivity of a component in a phase, fugacity is a measure of how much the chemical potential of the component in the gas deviates from the chemical potential of the pure substance in its standard state, due to changes in P and the mole fraction of the component. Therefore, f_{O_2} is a function of the mole fraction of the component in the gas phase and of the total pressure of the gas phase. A high f_{O_2} means a high chemical potential of oxygen, which indicates an "oxidized" system.

Oxygen Fugacity – Buffers:

Oxygen fugacity is a master variable used to describe geologic environments. Reducing conditions are "low f_{O_2} ", and oxidizing conditions are "high f_{O_2} ". However, thermodynamics is quantitative and, therefore, f_{O_2} must be well defined. In practice this is done by reference to well-known f_{O_2} buffers.

In the solar nebula, the most abundant O-bearing gaseous molecules were $H_2O(g)$, $CO(g)$, and $CO_2(g)$, assuming that chemical equilibrium was achieved. The f_{O_2} in such a system is controlled by the relative abundances of these molecules. For example, the f_{O_2} in a nebular system can be calculated using the ratio of $CO_2(g)$ to $CO(g)$ via:

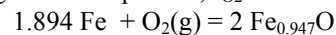


Using the equilibrium constant for this reaction (K_1), the f_{O_2} is expressed:

$$f_{O_2} = \left(\frac{f_{CO_2}}{f_{CO}} \right)^2 \cdot \frac{1}{K_1}$$

Since gaseous molecules dominated the inner region of the solar system during the formation of meteoritic components, the variation in oxidation states observed in unequilibrated chondrites suggests that either: 1) these components formed in separate regions of the solar nebula or 2) these components did not equilibrate with the nebular gases.

On asteroids, f_{O_2} may have been controlled by solid mineral buffers. For example, when both iron metal and the iron oxide wustite ($Fe_{0.947}O$) are present as pure homogenous compounds, f_{O_2} is buffered by:



In this case, f_{O_2} is expressed:

$$f_{O_2} = \frac{1}{K_2}$$

Thus, the oxidation states of equilibrated chondrites are a reflection of the oxygen fugacity established on the parent asteroid.

Correlation of Oxidation State with Thermal Metamorphism in Ordinary Chondrites. C. A. Marsh¹ and D. S. Lauretta¹, ¹University of Arizona, Lunar and Planetary Laboratory, Tucson, AZ 85721, USA (celinda@lpl.arizona.edu)

Introduction: All meteorites retain evidence of a heating event or events that occurred within the first few Ma of the appearance of the first solids in our solar system [1]. In chondrites the degree of thermal alteration or metamorphism experienced is measured through a classification system called petrologic type [2]. Heating of asteroids through the decay of ²⁶Al has been robustly studied and is generally favored as the heating mechanism for chondrite parent bodies [3]. Induction heating has been proposed as an alternate heating source [4]. While it has come under sharp criticism for requiring parameters that did not fit observations of T-Tuari winds [5], the induction heating mechanism has never been disproved [3].

Observations of Oxidation State: Conflicting reports on changes of oxidation state with thermal metamorphism have been made over the years e.g. [6, 7]. While direct measurements of oxygen fugacity with petrologic type have been made, those authors only inferred a reduction trend with metamorphic grade based on bulk abundances of Fe metal and Ni compositions in metal measured by others [6]. The ratio of Olivine (Ol) to low-Ca pyroxene (Opx), bulk Fe-rich metal abundances and Ni and Co abundances in metal were used to infer increasing oxidation with petrologic type [7, 8]. The presence of varying amounts of oxidizing vapor derived from accreted ices has been proposed to explain this trend [7]. However, this hypothesis has been criticized because of the lack of oxygen isotope variation between metamorphic grades, which would be expected if varying amount of ice were present [9].

New Measurements: We have developed a rapid calibrated mapping technique to make measurements of major element compositions in olivine and pyroxene. Maps covering a 1.28 by 1.28 mm region with 10 µm diameter pixels have been collected using a Cameca SX50 electron microprobe. The map regions are selected such that they are not dominated by a single large chondrule, but rather contain a number of chondrules as well as matrix material. The pixels are sorted using Si wt% and then filtered for appropriate total wt%. The ratio of olivine to low-Ca pyroxene pixels from a suite of L chondrites is reported in Table 1.

Table 1:

Meteorite	Class	Ol/Opx ratio
LEW 87284	L3.6	0.59
ALH 77197	L3.7	6.16
ALH 85045	L3.8	1.74
ALH 85033	L4	1.75
Saratov DL	L4	0.77
Saratov LL	L4	1.16

Our results cover a different range of petrologic type than has been previously been reported. We found one L3, ALH77197 to be strangely low in pyroxene abundance. Saratov DL and LL refer to a dark and light lithology visually observed on the same sample of Saratov. The percent mean deviation and mean composition of both olivine (PMD = 4%, mean Fe wt % = 16) and low-Ca pyroxene (PMD = 8%, mean Fe wt% = 11) in these two regions was within error. However, we found that the olivine to orthopyroxene ratio from these two regions, varies by more than 0.3. The total change in olivine to orthopyroxene ratio between L4s and L6s is less than 0.3 [7,8]. While our results are preliminary, they do not support a correlation between metamorphic grade and oxidation state.

References: [1] Keil, K. (2000) *Planet. Space Sci.* 48: 887-903. [2] Van Schmus, W.R. and Wood, J.A. (1967) *GCA* 31: 747-765. [3] McSween, H.Y., Ghosh, A., *et al.* (2002) In *Asteroids III*. [4] Sonett, C.P., Colburn, D.S., *et al.* (1970) *Astrophys. and Space Sci.* 7: 446-&. [5] Wood, J.A. and Pellas, P. (1991): In *The Sun in Time*. [6] Brett, R. and Sato, M. (1984) *GCA* 48: 111-120. [7] Mcsween, H.Y. and Labotka, T.C. (1993) *GCA* 57: 1105-1114. [8] Gastineau-Lyons, H.K., McSween, H.Y., *et al.* (2002) *Meteoritics & Planet. Sci.* 37: 75-89. [9] Wasson, J.T. (2000) *Rev. Geophys.* 38: 491-512.

METEORITE-ASTEROID LINKS: CAN THEY BE FORGED? T.J. McCoy¹ and T.H. Burbine² ¹Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560-0119 USA (mccoy.tim@nmnh.si.edu), ²Astronomy Department, Mount Holyoke College, South Hadley, MA 01075

Building the Chain: Born as scientific disciplines within six years of each other at the end of the 18th century, meteoritics and asteroid astronomy are intimately linked. Links between asteroids and meteorites satisfy both our basic curiosity as to the origin of these rocks and allow both communities to address the range of materials and processes operating during Solar System formation. In particular, identifying the parent asteroids for meteorites would elucidate compositional or thermal gradients present in the solar nebula. An excellent recent overview of meteorite-asteroid links is provided by [1] and is heavily referenced here. I review the disparate datasets used by asteroid astronomers and meteoriticists, discuss the merits of several such links, and point to directions for future research.

The Tools of the Blacksmiths: The key obstacle to asteroid-meteorite links is the nature and precision of data used by meteorite and asteroid scientists. Meteoriticists group objects from a common parent body primarily on the basis of extremely precise analyses of bulk chemistry, often for trace elements; mineral compositions, which mirror bulk chemistry; oxygen isotopes, which fingerprint unique nebular reservoirs; and cosmic-ray exposure ages, which point to liberation during a common impact event. In contrast, asteroid astronomers primarily use reflectance spectra to infer, through laboratory analysis of samples, approximate mineral abundances and, in some cases, mineral compositions. Knowledge of meteorite delivery mechanisms can point to the most promising main belt asteroids and complementary data (e.g., radar, spacecraft data) exist for small numbers of asteroids. Meteorite and asteroid datasets rarely overlap and uncertainties often prevent confident matches.

The Weakest Link?: Four asteroid-meteorite links are examined in order of increasing degree of confidence.

M asteroids/Irons/E chondrites The relatively featureless, red-sloped M asteroids are similar to spectra for both irons and E chondrites and have lower albedo and lack the ~0.5 μm feature observed in E asteroids [2]. High radar returns are consistent with highly-porous irons or non-porous E chondrites, although low densities may preclude an iron analog. This case illustrates the difficulty of establishing asteroid-meteorite links without spectral absorptions.

C asteroids/CM chondrites The link between C asteroids (e.g., 19 Fortuna) and CM chondrites is supported by the presence of a 0.7 μm spectral feature, the presence of C asteroids near the 3:1 resonance, and relatively low CRE ages. In this case, limited data provides a compelling link.

Vesta/HED's The link between 4 Vesta and HED's is the only one between a specific asteroid and meteorite group to be widely accepted, largely on the basis of spectral similarity; existence of a large, intact asteroid; and linkage of

Vesta to meteorite-delivery resonances through small Vestoids likely derived from a polar impact basin on Vesta. The Vesta-HED link may not be solid. Ibitira [3] appears to and NWA 011 does differ from other eucrites and may sample different parent bodies. Additional space-weathered basaltic asteroids have been identified among the S-class [4], including 17 Thetis with an average semi-major axis close to the 3:1 resonance that delivers meteorites to Earth.

S(IV) asteroids/Ordinary Chondrites The long-debated link between S asteroids and ordinary chondrites came to the forefront with the NEAR mission to 433 Eros. Despite exhaustive analyses, uncertainties in calibration and inadequate knowledge of regolith formation made it impossible to confidently distinguish whether Eros was composed of a partially-melted primitive achondrite or a space-weathered ordinary chondrite. This debate continues [5,6], although a space-weathered ordinary chondrite seems favored, with no consensus as to chemical group (H, L, LL).

The desire to match specific asteroids to meteorites may be futile, particularly as the number of meteorite groups (with concomitant decrease in the differences between them) and characterized asteroids increase. Our best option remains links between types of meteorites and classes of asteroids, with the best matches for those meteorites and/or asteroids that are compositionally anomalous (e.g., Angrites).

Stoking the Fire: Pointing to sample return missions as the ultimate solution would be misguided. Missions will never visit even a fraction of asteroid types and resolve questions about stratification in the asteroid belt. A unique contribution that missions can accomplish is the return of regolith, particularly a core sample including the optical regolith, to understand its unique formation and properties.

Ultimately, meteoriticists and asteroid scientists need to better focus on complementary data. Asteroid spectroscopists need better calibration curves for mineral compositions and proportions in multi-mineral mixtures, better characterization of samples used for spectral analyses, and additional data sets (e.g., radar). Meteoriticists need accurate silicate modes and bulk major element compositions in all meteorite types. Finally, both communities should form and foster active collaborations, funded by NASA in recognition of the importance of cross-disciplinary research, to address question of Solar System evolution.

References: [1] Burbine T.H. et al. (2002) In *Asteroids III*, 653-667. [2] Clark B.E. et al. (2004) JGR, E02011. [3] Franchi I.A. and Greenwood R.C. (2004) Oxygen in the Terrestrial Planets, Abst. 3048, [4] Sunshine J.M. et al. (2004) MAPS 39, 1343-1357. [5] McFadden L.A. et al. (2005) LPSC, #1561. [6] Foley C.N. et al. (2005) LPSC, #2017.

CORRELATIONS OF $\Delta^{17}\text{O}$ WITH CHEMICAL CHARACTERISTICS AMONG CHONDRITE GROUPS.D. W. Mittlefehldt, NASA/Johnson Space Center, Houston, TX 77059, USA (david.w.mittlefehldt@nasa.gov).

Introduction: Demonstration of mass-independent O isotopic variations in solar system materials was a seminal discovery of meteoritics. These variations were thought to reflect incomplete mixing of O from different nucleosynthesis sources [1]. Since then, two non-nucleosynthetic causes have been suggested: (i) differential photodissociation of distinct isotopomers of CO, enriching nebular gas in chemically reactive heavy O [2], and (ii) gas-phase molecular reactions producing mass-independent O isotopic exchange [3]. Nebular processes caused chemical fractionations that are observed in chondrite bulk compositions [4]. If nebular processes also produced mass-independent O isotopic variations, then these may correlate with chondrite bulk chemistry.

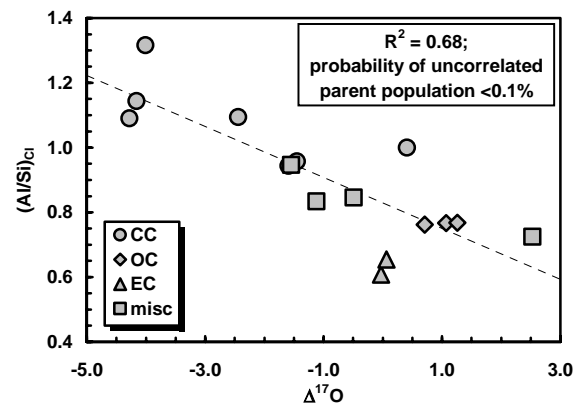
Models: Three models invoked to explain O isotopic heterogeneity in solar system materials are summarized in the table. The photodissociation model has several variants with different locations where photodissociation occurs [2, 5]. The predictions given in the table are for the model favored by Clayton [2, 6], which assumes the Sun is enriched in ^{16}O . This may [7], or may not [8], be the case. The molecular reactions model does not allow for clear predictions [3].

model	proponent	carrier	predictions
incomplete mixing	Clayton et al. [1]	high-T solids: ^{16}O -rich	no correlation with low T chemistry
photo-dissociation	Clayton [2, 6]	H_2O gas: ^{16}O -poor	possible correlation with high-T and low-T chemistry
molecular reactions	Thiemens [3]	several gas species	unclear

Chondrites: Negative correlations exist between CI-normalized refractory-lithophile-element/Si or Mg ratios and $\Delta^{17}\text{O}$ among chondrite groups (figure). Although correlation coefficients (R^2) are typically only ~0.55-0.70, the probabilities that the data could reflect an uncorrelated parent population are typically <0.5%. This is impressive considering averaged chondrite data were used, and that the bulk compositions and O isotopic data were not determined on identical suites of samples. These correlations are consistent with incomplete mixing and photodissociation models. Refractory-siderophile elements show a similar trend – Ir/Ni decreases with increasing $\Delta^{17}\text{O}$. This could reflect mixing of differing amounts of ^{16}O -enriched CAI-like components into bulk chondrites à la the incomplete mixing model or the photodissociation model.

There are also weak positive correlations of moderately-volatile-lithophile-element/Mg ratios. Mass balance shows this is not due to dilution by volatile-poor, ^{16}O -enriched CAIs – *i.e.* simple mixing cannot explain the correlation. The trend could indicate evolution of reactive nebular gas to more $^{17,18}\text{O}$ -enriched compositions with falling temperature. The situation is complex for moderately-volatile-siderophile elements. For most chondrite groups, Ga/Ni increases with $\Delta^{17}\text{O}$ as is the case for Na/Mg. However, ordinary and R chondrites are distinctly depleted in Ga/Ni compared to that trend. Thus, nebular temperature and O isotopic composition are not linked in a simple way, and factors such as nebular location relative to sites of O isotopic fractionation may have been important.

The correlations include the highly reduced EH and EL chondrites, which are believed to have formed in a much more reduced nebular region of different composition [9]. EH and EL chondrites are devoid of FeO, eliminating simple oxidation of metal by heavy H_2O as the cause of their O isotopic composition. This may support the molecular reactions model, in which isotopic anomalies are transferred to gas species such as SiO [3] that are the building blocks of condensates.



References: [1] Clayton R.N. et al. (1973) *Science*, 182, 485-488. [2] Clayton R.N. (2002) *Nature*, 415, 860-861. [3] Thiemens M.H. (1999) *Science*, 283, 341-345. [4] Palme H. and Jones A. (2004) *Treatise on Geochemistry*, vol. 1, 41-62. [5] Yurimoto H. and Kuramoto K. (2004) *Science*, 304, 1763-1766. [6] Clayton R. N. (2005) *LPS XXXVI*, Abstract #1711. [7] Hashizume K. and Chaussidon M. (2005) *Nature*, 434, 619-622. [8] Ireland T.R. et al. (2005) *LPS XXXVI*, Abstract #1572. [9] Kallemeyn G.W. and Wasson J.T. (1986) *Geochim. Cosmochim. Acta*, 50, 2153-2164.

DETERMINING THE EFFECTS OF AQUEOUS ALTERATION ON THE DISTRIBUTION OF OXYGEN ISOTOPES IN CARBONACEOUS CHONDRITES. A. A. Morris, L. Baker, I.A. Franchi and I.P. Wright. Planetary and Space Science Research Institute, The Open University, Milton Keynes, MK7 6AA (a.a.morris@open.ac.uk)

Introduction: Carbonaceous chondrites play a key role in determining the history of the early Solar System; a knowledge of the oxygen isotope variation within these materials will not only help in our understanding of the origin and evolution of those meteorites, but also the early Solar System reservoirs from which they formed [1].

However, several problems present themselves when trying to interpret early Solar System history. One is identifying the isotopic signature of oxygen from specific component compounds in a complex mixture of materials that existed in the solar nebula, and deconvoluting this from signatures developed during parent body processing (e.g. aqueous alteration, thermal metamorphism). Only then is it possible to develop an understanding of the nature and conditions of these secondary processes.

Background: Of all the meteorite groups the carbonaceous chondrites (particularly the CI, CM and CR meteorites) have the most diverse range of high and low temperature mineral phases, and display the widest range of oxygen-isotopic compositions [1,2]. Volumetrically, much of these meteorites consists of a very fine grained matrix material composed largely of low temperature alteration minerals but intimately mixed with a fine grained fraction of the anhydrous, isotopically distinct phases [3]. A full understanding of the oxygen-isotopic systematics between these different phases is required in order to constrain the processes that led to their formation [3]. However most previous oxygen isotope studies have concentrated on the silicate portions which in the case of the matrix means studying complex mixtures [3,4]. Aqueous reactions can not only promote chemical redistribution and changes in petrological relationships but also generate large isotopic fractionation of oxygen isotopes [5].

Models to account for the variations in oxygen-isotopic compositions in carbonaceous chondrites e.g. [6,7] generally involve mixing of a solid anhydrous silicate component, with an isotopic composition enriched in ^{16}O , with liquid water depleted in ^{16}O along with mass-dependent isotopic fraction between various phases at low temperature [3]. Isotopic evolution of the fluids involved in these reactions would be expected to lead to significant isotopic heterogeneity within the components e.g. [7].

Recent studies have shown that structural water (OH^-) can be extracted from phyllosilicate components in the CM meteorites by incremental heating, and used for oxygen isotope measurements. This also provides the ability to resolve oxygen from a number of different components within the complex mixture of minerals in the matrix of these meteorites [3,4]. The (OH^-) from the CM phyllosilicates is found to have a similar $\Delta^{17}\text{O}$ to co-existing carbonates, analysed by [8] indicating that they formed from the same fluid reservoir, and may in fact have formed in isotopic equilibrium.

We are employing a number of approaches to better determine the distribution of oxygen isotopic components within these complex meteorites. Stepped heating extraction to liberate water and structural (OH^-) permits isotopic measurements of resolved components [4], the identification of which is being established by a detailed study of the thermal release temperature of water (OH^-) components from meteorites and a range of terrestrial analogues. Artificial weathering experiments using isotopically labeled water are being used to trace the location of different oxygen reservoirs as alteration proceeds.

Such data may then be used to constrain temperature of equilibrium between the phyllosilicates and carbonates minerals and water-rock ratios involved; important constraints for evolution models of carbonaceous chondrites [6,7].

Summary: The initial stepped heating experiments for carbonaceous chondrites revealed considerable variation in $\delta^{18}\text{O}$ [3]. Much of our new work is aimed at determining the extent of isotopic fractionation associated with the formation of the common phyllosilicates found in meteorites, and identifying the specific minerals liberating (OH^-) at each temperature.

This will be used ultimately to better constrain the isotopic composition of the fluids involved in the alteration process.

- [1] Clayton R. N. & Mayeda T. K. (1999) *GCA*, 63, 2089–2104. [2] Brearley A. J. & Jones R. H. (1998) *Planetary Materials*, 36, 3-01-3-370. [3] Franchi. *et al* (2001) *Phil. Trans. R. Soc. Lond. A* 359, 2019–2035. [4] Baker. *et al*. (2002) *Analyt. Chem.* 74 1665-1673 . [5] Zolensky M. & McSween H. Y. (1988) *Meteorites and the Early Solar System*, 114-144. [6] Clayton R. N. & Mayeda T. K. (1984) *EPSL*, 67, 151-161. [7] Young E. D. *et al*. (1999) *Science*, 286, 452-455. [8] Benedix. *et al*. (2000) *LPSC XXXI* Abs #1840

SPACE WEATHERING ON ASTEROIDS S. K. Noble¹, ¹U.S. House of Representatives, House Committee on Science, 394 Ford Building Washington D.C. noble@porter.geo.brown.edu.

Introduction: “Space weathering” is a blanket term that is used to describe the processes and products by which physical and optical changes are incurred by a surface exposed to the harsh environment of space. Our understanding of space weathering comes almost exclusively from studies of lunar soils. The array of space weathering processes in the lunar regolith are illustrated in Fig. 1 [1, as modified from 2].

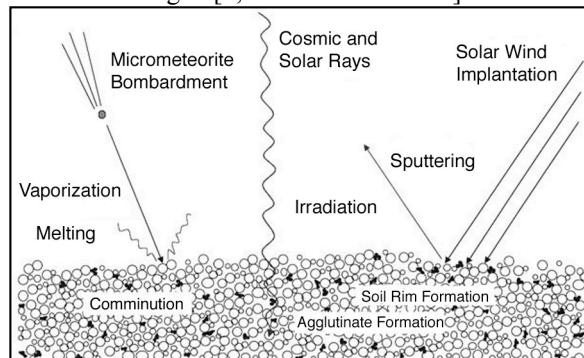


Figure 1. The major processes and products associated with space weathering.

There are two main products produced by space weathering: rims and agglutinates. Detailed microanalyses [3, 4] have shown very thin (60-200 nm) patinas, or rims, developed on individual lunar soil grains from mature soils. These rims are created by both subtractive (radiation damage) and additive (vapor deposition and solar wind sputtering) processes. The rims often contain abundant single domain metallic iron particles, referred to as nanophase iron (npFe⁰) [3] or SMFe [5]. The other major product of space weathering is agglutinates. These glass-welded aggregates also contain npFe⁰.

The Importance of Space Weathering: Since remote sensing methods generally do not sample the pristine rocks of the body, but rather the exposed regolith, it is imperative to understand the processes by which rocks become soils, and specifically, the effects of soil formation processes on the properties of a soil in order to get accurate results from remote datasets. Understanding space weathering is important because the products produced by space weathering have distinct and predictable effects on the optical properties of soils [5,6]. The optical effects on lunar soils, the so-called “space weathering continuum”, is largely the result of the accumulation of npFe⁰. These effects have traditionally been described as threefold: weathering causes the reflectance spectra in the vis-nearIR to be both darker and redder, and also results in an attenuation of the characteristic absorption bands. Recent work has shown that the process is more complex than simply

“reddening” and “darkening”, rather, as a soil acquires npFe⁰, its continuum changes in a regular and predictable way [7].

Space Weathering on Asteroids: In general, the spectra of asteroids do not match the spectra of our collection of meteorites. Particularly, the spectra of S-type asteroids, the most abundant type, do not correspond well to the spectra of the most abundant type of meteorites, ordinary chondrites (OCs). The asteroid spectra tend to be redder than the meteorites with a steep curvature in the visible wavelengths. It has been suggested by many [e.g. 6,8,9] that this spectral mismatch is the result of space weathering.

In the asteroid belt, the environment is significantly different than lunar conditions. Collisions are on average slower, so micrometeorite bombardment will cause less melting and considerably less vaporization than on the Moon. Also, as the distance from the sun increases, the solar wind particle flux decreases, thus less sputtering and implantation occurs. Finally, the impact rate is greater, comminuting fresh material at a faster rate and diluting any weathering products. These arguments suggest that soils on asteroids will accumulate npFe⁰ at a significantly lower rate than those on the Moon. Studies of regolith breccia meteorites support this conclusion: weathering products such as npFe⁰-bearing rims [10] and agglutinates [11] are found to be extremely rare (but not absent) in these lithified asteroidal regoliths.

However, even very small degrees of space weathering can have quite dramatic consequences for the optical properties of soils [10]. The shape of the space weathering continuum is strongly dependent on the amount of npFe⁰ present. Very small amounts of npFe⁰ result in a strong curvature in the visible, while the near-IR remains nearly unaffected.

Conclusions: The optical effects of very small degrees of space weathering differ substantially from the more general reddening/darkening effects of larger amounts of weathering. These trends can account for most differences observed between ordinary chondrite and S-type asteroid spectra.

References: [1] Noble S. K. (2004) PhD Thesis [2] Housley R. M. (1973) 4th PLPSC 2737-49. [3] Keller L. P. and McKay D. S. (1997) *GCA* **61**, 2331-41. [4] Wentworth S. *et al.* (1999) *MaPS*, **34**, 593-603. [5] Hapke. B. (2001) *JGR*, **106** E5, 10,039-10,073. [6] Pieters C. M. *et al.* (2000) *MaPS*, **35**, 1101-1107. [7] Noble S. K. *et al.* (2001) *MaPS*, **36**, 31-42. [8] Binzel R. *et al.* (1996) *Science*, **273**, 946-948. [9] Chapman C. R. (1996) *MaPS*, **31**, 699-725. [10] Noble S. K. *et al.* (2004) *LPSCXXXV* ab# 1301. [11] Basu A. and McKay D. S. (1983) *Meteoritics*, **18**, 263-264.

OH AND H₂O ON ASTEROIDS: AN ASTRONOMICAL PERSPECTIVE

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The vast majority of meteorite parent bodies are thought to reside in the asteroid belt. In addition to the known samples in the collections, there is a large amount of unsampled material among the asteroids. Because of the current impracticability of sampling a large number of asteroids via space mission, remote sensing techniques have been developed to determine asteroidal compositions from ground-based (and occasionally space-based) observations.

In the 35 years since the first modern asteroid spectra were published, a large amount of data have been collected, which provide us with direct and/or indirect evidence of the presence of phyllosilicates, oxidized and reduced forms of iron, pyroxene and olivine, troilite, and other minerals on asteroidal surfaces.

I will address what these observations tell us about the oxygen distribution and low-temperature processes in the asteroid belt, focusing on what we've learned about hydroxyl/water-bearing minerals, but also touching on other relevant data as appropriate.

RELICT OLIVINE, CHONDRULE RECYCLING, AND EVOLUTION OF OXYGEN RESERVOIRS. A. Ruzicka¹, H. Hiyagon² and C. Floss³. ¹Portland State University, Dept. of Geology, Portland, OR 97207, USA., ²Dept. of Earth and Planetary Physics, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, ³Washington University, Laboratory for Space Science, Campus Box 1105, St. Louis MO 63130, USA.

Introduction: Using SIMS techniques we have analyzed oxygen isotopes and trace elements in relict olivine grains [1], together with co-existing overgrowths and normal olivine, within chondrules of the Chainpur (LL3.4) and Sahara 97210 ("Sahara", LL3.2) chondrites. As relict olivine grains predate the formation of host chondrules, they provide an opportunity to study how chondrule components evolved.

Results: Fig. (a-c) shows standard 3-isotope oxygen plots for selected data we have obtained. Typical ordinary chondrite materials (OCM) cluster around the average compositions of equilibrated H-, L- and LL-chondrites and are distinct from the carbonaceous chondrite anhydrous materials (CCAM) line [2,3].

Magnesian olivine relicts enriched in ¹⁶O. Fig. (a) shows that some magnesian relict olivine grains, including refractory forsterites (RFs) and other anomalous Mg-rich grains, are distinctly enriched in a ¹⁶O component compared to more ferrous olivine in the chondrules. These data are consistent with the idea that nebular reservoirs evolved over time to heavier oxygen compositions [2-5].

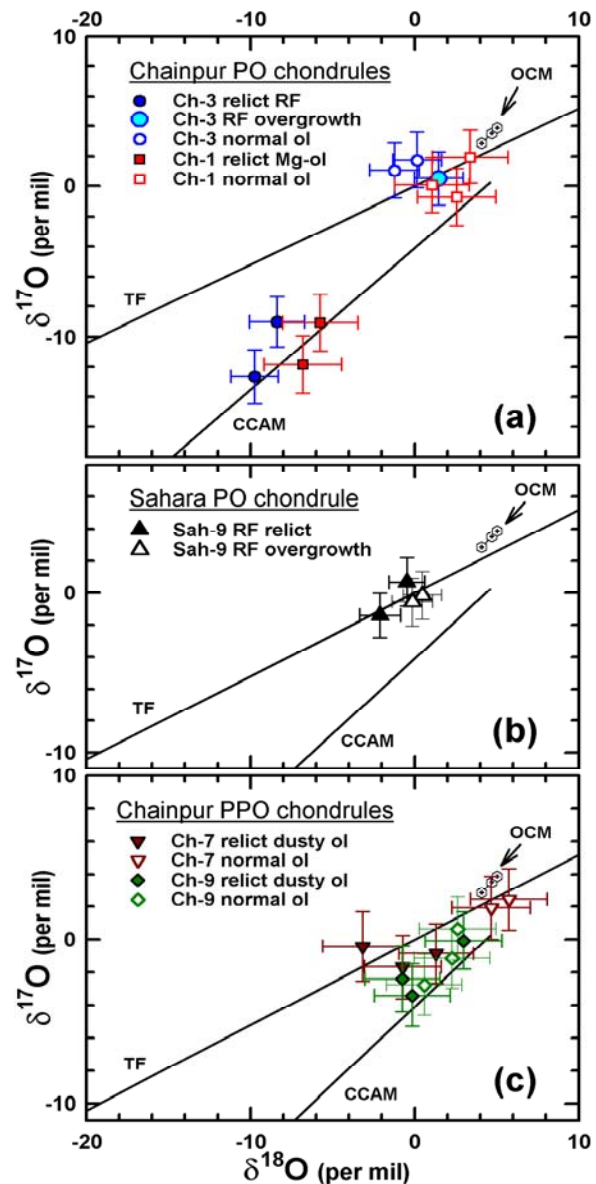
Magnesian olivine relicts not enriched in ¹⁶O. The O-isotopic compositions of some Mg-olivine grains are similar to co-existing ferrous grains and lie close to the terrestrial fractionation (TF) line (Fig. b). The relict RFs in Sah-9 and Ch-3 have similar major- and trace-element compositions, yet very different O-isotopic compositions (Fig. a, b). This suggests that chemical and isotopic compositions of chondritic olivine may be strongly decoupled, in contrast to the models of others [4,5].

Dusty olivine relict grains. Fig. (c) indicates that dusty and normal olivine grains have overlapping O-isotopic compositions with no evidence of a difference between them in $\Delta^{17}\text{O}$. There is a hint of mass fractionation between dusty and normal olivine in Ch-7 but not in Ch-9. The similar $\Delta^{17}\text{O}$ values between dusty relicts and normal olivine are consistent with a reduction reaction to form dusty olivine from more ferrous olivine during chondrule recycling [6].

Chondrule recycling. Taken as whole, our data can be understood if chondrule precursors were recycled during chondrule formation under different conditions. Some Mg-olivine, dusty olivine, and Fe-olivine formed when oxygen reservoirs were isotopically heavy and approaching the composition in which

OCM formed; other, possibly earlier, Mg-olivine formed when the reservoir composition was isotopically light and similar to that in which carbonaceous chondrites formed.

References: [1] Jones R.H. (1996) *Chondrules in the Protoplanetary Disk*, 163-172. [2] Clayton R.N. et al. (1991) *GCA* 55, 2317-2337. [3] Clayton R.N. (1993) *Annu. Rev.* 21, 115-149. [4] Kunihiro T. et al. *GCA* 68, 3599-3606. [5] Pack A. et al. (2004) *GCA* 8,1135-1157. [6] Jones R. and L.R. Danielson (1997) *MAPS* 32, 753-760.



Eu Valence Oxyparameter in Pyroxenes. Effects of Pyroxene Composition-Crystallization Histories-Crystallization Kinetics and a Comparison Between Lunar Basalts and Eucrites. Shearer, C. K., Papike, J. J., and Karner, J. M. Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131-1126 cshearer@unm.edu.

Introduction: Lunar basalts and eucrites are thought to crystallize at f_{O_2} conditions below IW. The FeO contents of these basalts have been interpreted as indicating that both basalts crystallized at IW-1 [1]. To better understand potential subtle differences among lunar basalts and between lunar basalts and eucrites, we are investigating the behavior of multivalent cations (Eu, V) in pyroxenes. The behavior of Eu in martian basalts has been demonstrated to be an effective measure of f_{O_2} [2]. Here, we compare the Eu/Eu* in pyroxenes from the more reducing environments of the Moon and the HED parent body, evaluate the dependence of Eu/Eu* on pyroxene composition-crystallization sequence-crystallization kinetics and contrast the relationship between Eu/Eu* and V.

Pyroxenes in Lunar Basalts and Eucrites: To compare Eu/Eu* in lunar basalts and eucrites and to better understand the variables that may affect this indicator of f_{O_2} in basalts, we selected four nearly isochemical lunar pigeonite basalts (15058, 12021, 12052, 15499) and Pasamonte, an unequilibrated eucrite. The lunar basalts have experienced different cooling [3] and crystallization [4] histories. Basalt 15499 cooled at a rate of 5 to 20°C/hour, whereas 15058 cooled at a rate of < 1°C/hour [3]. The two other lunar basalts and Pasamonte have intermediate cooling rates. Variations in pyroxene chemistry are partially illustrated in Figure 1. The incoming of plagioclase is reflected in the pyroxene by Ca, Al, and Ti/Al. The Al and Ti/Al in the pyroxene in Pasamonte reflect co-crystallization of plagioclase, in 15499 they reflect near absence of plagioclase crystallization, and in the other lunar basalts plagioclase co-crystallization occurs after variable amounts of pyroxene crystallization.

f_{O_2} and the Eu/Eu* in pyroxene: Of the lunar basalts analyzed, 15058 has the slowest cooling rate, exhibits the widest range of major element zoning, and has substantial co-crystallization of pyroxene and plagioclase (Figure 1). Although the lunar basaltic melts are enriched in Eu²⁺ relative to Eu³⁺, the earliest pigeonites have a calculated Eu²⁺/Eu³⁺ of approximately 0.03. These early pyroxenes have a Eu/Eu* of approximately 0.4 -0.5. This value decreases with increasing Ca and eventually reaches 0.2 -0.3 in high-Ca pyroxene which co-crystallizes with plagioclase. This value stays constant throughout plagioclase crystallization. It is unclear at this time whether the changing

Eu/Eu* is a function of Ca in the M2 site or plagioclase reaching the liquidus. Early pigeonite in Pasamonte has a calculated Eu²⁺/Eu³⁺ similar to that of the early pigeonite in 15058. The Eu/Eu* of the pigeonite overlaps with that of the early pigeonite in 15058 and does not radically change with increasing Fe and Ca. This overlap in Eu/Eu* appears unusual due to differences in the timing of plagioclase crystallization and suggests slight differences in f_{O_2} . This needs to be explored further. Plagioclase in lunar basalts and eucrites appear to have similar Eu/Eu* [5].

f_{O_2} , V, and V/Sc in pyroxene: In addition to Eu, V valence changes over a range of f_{O_2} and affects V partitioning behavior[6]. A companion abstract illustrates the usefulness of V in pyroxenes as an indicator of f_{O_2} [7]. In the lunar pyroxenes, V increases with Ca and then substantially decreases with Fe. V partitions differently between growth surfaces normal to (110) and (010). V/Sc consistently decreases from early to late pyroxene. V and V/Sc in the early pigeonite from Pasamonte are lower than the early pyroxene from the Moon. In the pyroxenes from Pasamonte V and V/Sc decrease slightly with increasing Ca and Fe.

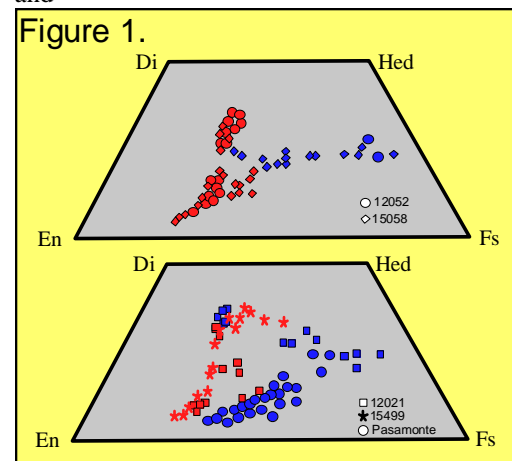


Figure 1. Pyroxene quadrilateral illustrating crystallization trends in the different basalts used in this study. Blue symbols indicate pyroxenes that crystallized with plagioclase, whereas red symbols indicate pyroxenes that crystallized prior to plagioclase.

References: [1] Jones, J. (2004) LPSC XXXV. [2] Wadhwa (2001) *Science*, 292, 1527-1530. [3] Lofgren et al. (1975) Proc. 6th Lunar Sci. Conf., 79-99. [4] Bence and Papike (1972) Proc. 3rd Lunar Sci. Conf., 431-469. [5] Karner et al., (2004) Am. Min. 89, 1101-1109. [6] Papike et al. (2005) Am. Min., 90, 277-290. [7] Karner et al. (2005) this volume.

A CHEMICAL MODEL OF MICROMETEORITE IMPACT INTO OLIVINE. A. A. Sheffer and H. J. Melosh, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, abigailw@lpl.arizona.edu, jmelosh@lpl.arizona.edu.

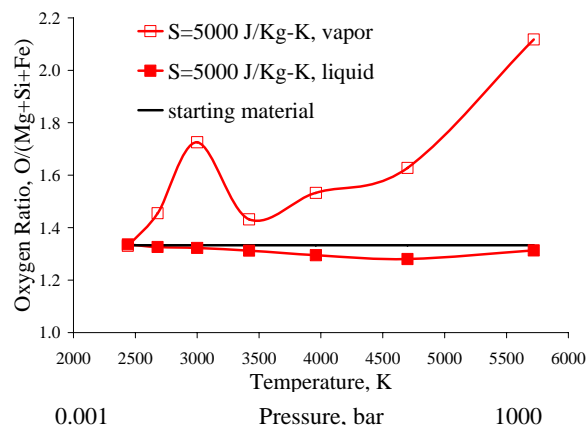
Introduction: Laboratory simulations of space weathering using laser irradiation have been successful in reproducing space weathering characteristics such as the reduction of olivine to form nanophase iron particles [1,2]. However, the chemistry of the reduction of Fe^{2+} in olivine to Fe metal has not been fully explored. We present a thermodynamic model of olivine undergoing post-impact cooling and decompression.

Shock Melting: The cooling path of rocks melted by hypervelocity impact is much different than for rocks melted at a constant pressure [3]. A strong shock causes both the pressure and temperature to jump to very high values. Since the shock compression is irreversible, the rock's entropy also jumps. Decompression is isentropic, thus cooling follows a specific P-T path.

Modeling: The equilibrium module in the HSC Chemistry package [4] was used to model the Gibbs energy minimization. Equilibrium compositions were computed for the pressures 0.001, 0.01, 0.1, 1, 10, 100, 1000, and 10000 bars over the temperature range 1500-6000 K. Entropy calculations were performed in Excel. We used the composition of Fa_{10} similar to the San Carlos olivine used in [1,2] as a starting composition. Only the elements Si, Mg, Fe, and O were included in the model.

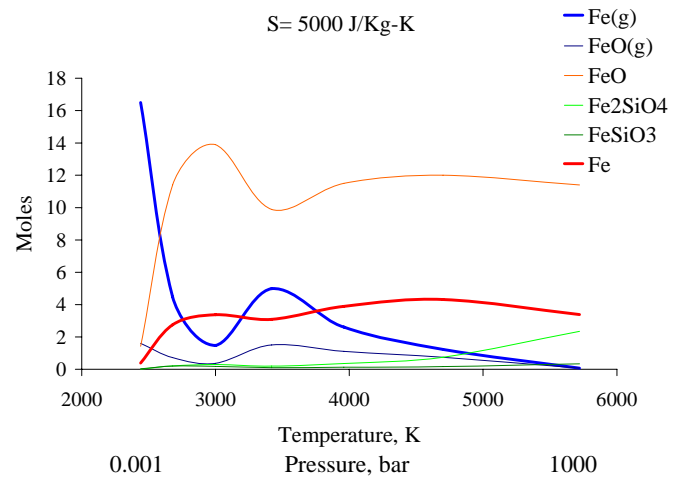
Results: We modeled the isentropic cooling path for $S = 5000 \text{ J/K}\cdot\text{kg}$. This is an intermediate value in the range ($S=3000$ to $6000 \text{ J/K}\cdot\text{kg}$) required to vaporize forsterite but allow formation of a liquid upon decompression and cooling.

The ratio of moles of O to moles of Si, Mg, and Fe is an indicator of oxygen enrichment. The higher the number, the more oxygen is available for bonding with the other elements. The starting material value is 1.33.



Except for at the lowest temperature and pressure, the vapor phase at this entropy contains a higher ratio of oxygen to other elements than the liquid phase or the starting material. Therefore, any loss of vapor would leave the liquid reduced compared to the starting material.

The dominant equilibrium species along the correlated P-T path are MgO and MgSiO_3 . At the lowest temperature and pressure, $\text{Mg}_{(\text{g})}$, $\text{O}_{(\text{g})}$, and $\text{SiO}_{(\text{g})}$ become the most abundant species. The Fe-bearing species are plotted below. Fe metal is present in the liquid phase for the entire cooling path, but $\text{Fe}_{(\text{g})}$ is also present for the majority of the cooling path.



Discussion: Since both Fe metal and $\text{Fe}_{(\text{g})}$ are present along the cooling path, droplets could form both inside the quenched glass and as a product of vapor deposition. These results support previous work that reducing agents are not necessary [1,2,5], and that micrometeorite impact can produce iron metal.

Future work will include modeling the isentropic cooling path of a bulk chondritic composition.

References: [1] Sasaki, S. et al. (2003) *Adv. Space Res.*, 31, 2527-2542. [2] Sasaki, S. et al. (2002) *Adv. Space Res.*, 29, 783-788. [3] Melosh H. J. and Artemieva N. (2004) *LPS XXXV*, Abstract #1732. [4] Eriksson G. and Hack K. (1990) *Metall. Trans.*, 21B, 1013-1023. [5] Hapke, B. (2001) *JGR*, 106, 10039-10073.

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EXPLORING THE ORIGIN OF PLANETARY WATER USING AN ATOMISTIC APPROACH. M. Stimpfl¹, M. J. Drake¹, D. S. Lauretta¹, P. Demyer². ¹Lunar and Planetary Laboratory, ²Material Science and Engineering; University of Arizona, Tucson, Arizona 85721-0092, U.S.A stimpfl@lpl.arizona.edu

The origin of Earth's water and, by extension, water in other inner solar system bodies has been long debated. Two main scenarios have been proposed to account for the delivery of water to the inner planets: either the water originated outside of the inner solar system and was later delivered to the terrestrial planets or the source of water was local and was concomitantly accreted to the accreting bodies. Isotopical and geochemical fingerprints seem to indicate that comets and asteroids alone could not have been the principal source of water for the Earth. Furthermore, these exogenous sources of water would have delivered the water, after the planet had reached more than 85% of its size, after core formation [1, 2]. However, such late delivery of water seems to be in contrast with geochemical requirements [3]. If the Earth acquired its water locally, this source of water could be represented by hydrous material that formed at 1 AU. Under this scenario, hydrous material was incorporated directly into the accreting Earth early on, thus influencing the geochemical behavior of elements partitioning between the mantle and the core, the oxidation state of the mantle, and also keeping the surface of the planet at a T high enough to sustain a magma ocean. However, most models of the solar nebula do not allow stable hydrous minerals at 1 AU [4].

We explore the role of adsorption onto grains prior to planetary accretion as a possible new mechanism that could bring water to the Earth. Monte Carlo simulation of adsorption at nebular T, P and $f_{\text{H}_2\text{O}}$ onto a flat surface showed that this mechanism can store on dust grains in the pre-accretion disk up to 3 times the Earth's oceans [5]. This model, however, did not take into account the specific surface interactions between water gas and the crystalline surface nor did it investigate rigorously the role of porosity. To fill this gap, we are performing molecular dynamics simulation of the system water and olivine using the code GULP [6]. The bulk olivine will be modelled using periodic boundary conditions (PBC) and Buckingham potentials for the short-range interactions with a cut off distance of 10 Angstroms for both short and long range interactions. The "virtual crystal" was then cleaved by removing the PBC in the positive z direction and thus creating a free surface. After the top layer relaxed we inserted water molecules and studied their trajectories. This simulation will allow construction of surface site adsorption probabilities and site energies at nebular T.

References: [1] Morbidelli A. et al (2000) *MPSL*, 35, 1309-1320. [2] Kleine T. et al. (2002) *Nature* 418, 952-955. [3] Abe Y. et al. (2000) *Protostars and Planet*, 413-433. [4] Cassen P. (1994) *Icarus*, 112, 405-429. [5] Stimpfl M. et al. (2004) *MAPS* 39, A99. [6] Gale J.D. (1997) *J. Chem. Soc. Faraday Trans.*, 93, 629-637.

THE HAYABUSA ASTEROID SAMPLE RETURN MISSION. H. Yano, Dept. of Planetary Science, Japan Aerospace Exploration Agency (JAXA)/Institute of Space and Astronautical Science (ISAS) 3-1-1 Yoshinodai, Sagami-hara, Kanagawa, 229-8510, JAPAN (yano.hajime@jaxa.jp).

Introduction: On 9th May 2003, the Japanese spacecraft MUSES-C was successfully launched from Uchinoura. The spacecraft was directly inserted into an interplanetary trajectory and renamed as “Hayabusa”, or “Falcon”, to be the first sample return spacecraft to visit a near-Earth asteroid (NEA) [1]. The target is NEA (25143)Itokawa (formerly known as 1998SF36). Its size is 490 (± 100) x 250 (± 55) x 180 (± 50) m with a ~12-hour rotation period [2]. It has a red-sloped S(IV)-type spectrum with strong 1- and 2-micron absorption bands, analogous to ordinary LL chondrites exhibiting possible space weathering effect [3]. The asteroid could be olivine rich compared to typical S asteroids. Assuming a bulk density of ordinary chondrites, the surface gravity of Itokawa is on the order of 10 micro-G, with an escape velocity = ~20 cm/s.

Mission Sequences: At present, the spacecraft operates with three ion propulsion engine systems. In June 2005, the spacecraft will be inserted into an orbit which is nearly identical to the orbit of the target asteroid itself. As it draws nearer the asteroid, the spacecraft will conduct global mapping with an multi-color optical camera, near-infrared spectrometer, X-ray fluorescence spectrometer, and LIDAR for up to three months

Sample Return Strategy: After completing global mapping, the first descent for touch-and-go sampling will be conducted. Before touching the surface, however, one of three target markers will be dropped to track its passage by autonomous navigation. Also a hopping rover called MINERVA will be deployed. Since the actual surface conditions of Itokawa are unknown, HAYABUSA employs a sampling mechanism that should work for a diverse heterogeneity of target surfaces, from hard metal-silicate surfaces to fluffy regoliths [4]. Within 0.3 seconds after the tip of the sampler horn touches on the asteroid surface, a Ta projectile of 5-g mass is shot at 300 m/sec by a small projector onto the asteroidal surface. Impact of the projectile produces surface ejecta, which is concentrated through a conical capture horn toward the sample catcher. The catcher is transferred into the reentry capsule, which is hermetically sealed. During testing, the mass of samples recovered ranged from several hundred mg to several g per shot. The majority of recovered samples were fine-grained (sub-mm size) particles, rather than large chips. The sampling will occur at as many as three locations in November 2005.

Preliminary Sample Analysis: In July of 2007 the samples will be returned to Earth within the hermetically-sealed capsule, and flown to a new dedicated curation/preliminary examination lab in Sagami-hara for ~1 year of preliminary investigation in Japan. During this time investigations of the

vestigations of the samples will be made by largely Japanese teams, though with some foreign participation. These teams are being chosen through competitions. A maximum of 15 mass% could be consumed to characterize representative samples during this 1-year long preliminary examination phase. Following the initial analysis period an international announcement of opportunity for detailed analyses of another 15 mass% of the samples will be released. Another 10 mass% will be transferred to NASA's Johnson Space Center.

References: [1] J. Kawaguchi et al. (2000) *Prof. 22nd ISTS*, 2000-o-3-06v. [2] M. Kaasalainen et al. (2002) *Proc. ACM 2002*, ESA SP-500. [3] R.P. Binzel et al. (2001) *Meteoritics & Planet. Sci.*, **36**. [4] J. Veveřka et al. (2001) *Science*, Vol. **292**, 484-488.

WHAT IS THE WATER (OH) CONTENT OF THE E ASTEROIDS? M.E. Zolensky, KT, NASA Johnson Space Center, Houston, TX 77058 USA (michael.e.zolensky@nasa.gov).

Introduction: Attempts to match the E asteroids with enstatite-rich meteorites universally conclude that the aubrites or enstatite chondrites are natural candidates, and accordingly conclude that E asteroids as a class are very water-poor [1]. Accordingly, the highly reduced nature of typical enstatite-rich meteorites suggests that aqueous alteration was an improbable process on any E asteroid. However, there are spectroscopic observations of several E-class asteroids that suggest the presence there of hydrated phases [2]. Examination of the Kaidun meteorite reveals the true situation.

Kaidun: The unique Kaidun meteorite completely consists of a disparate assemblage of extraterrestrial materials, ranging from carbonaceous chondrites, to ordinary chondrites, to basaltic achondrites, to enstatite chondrites [3]. All of these materials exhibit the complete range of alteration state, from fully anhydrous lithologies through to completely altered on a very fine scale. There are even clasts which are frozen in a state of half-altered and half-unaltered. This observation requires aqueous alteration to have occurred at a different location than the place of final assembly of Kaidun. Indeed, much if not most of the materials within Kaidun must have formed on many different asteroids, and possibly other bodies as well.

In most regards the EH lithologies in Kaidun are like the typical EH meteorites [1]: Enstatite, plagioclase, silica, Fe,Ni, schreibersite, troilite, niningerite and unusual Fe,Cr-sulfides are present, carbon and perryite are present but less abundant, oldhamite, sphalerite, djerfisherite, schöllhornite, daubreelite, roedderite and Ca,Fe-phosphate are rare. The critical feature is that hydrated phases are abundant in practically all EH lithologies in Kaidun, in contrast to all other

examples of EH chondrites which are entirely anhydrous.

There is evidence that E, C, and D asteroids, at the very least, provided the various materials now in Kaidun [3]. The mechanism for transport of these diverse materials to a single site on one parent asteroid must have involved numerous impacts. A record of some of these impact events remains in Kaidun in the form of melt clasts and shock melt veins, some even in carbonaceous chondrite lithologies. The Kaidun lithology clasts are micrometeorite-sized, and dynamical studies reveal that sampling of the solar system is much more representative for such small objects than for much larger meteorites [4]. Some EH chondrite lithologies in Kaidun show evidence of incomplete, late-stage aqueous alteration otherwise unknown from these classes of meteorites. This observation buttresses the spectroscopic data indicating the presence of water of hydration on some E-asteroids [1].

Water On the E Asteroids: Thus water was widespread throughout the early solar system, and not confined to regions beyond the putative snow line. Our perception that the E-asteroids are completely reduced and anhydrous are driven by the biased sampling we have from meteorites. Even the most reduced objects in the solar system could not escape periods of aqueous alteration, due to influx of hydrated bodies from heliocentric distances beyond the point where ice was, technically, stable.

References: [1] Keil (1989) *Meteoritics* **24**, 195-208; [2] Rivkin et al. (1995) *Icarus* **117**, 90-100; [3] Zolensky and Ivanov (2003) *Chemie de Erde* **63**, 185-246; [4] Gounelle et al., *GCA* in press.

COMPETITIVE OXIDATION AND HYDRATION DURING AQUEOUS ALTERATION OF ASTEROIDS. M. Yu. Zolotov¹, M. V. Mironenko³, and E. L. Shock^{1,2}, ¹Department of Geological Sciences, ²Department of Chemistry and Biochemistry, Arizona State University, Tempe, Arizona 85287, ³Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Kosygin Str. 19, Moscow 119991, Russia. E-mail: zolotov@asu.edu.

Introduction: Studies of chondrites show that incorporation of H₂O ice during formation of asteroids followed by radioactive heating caused partial oxidation and hydration of primary reduced and anhydrous rocks [1-3]. Oxidation of kamacite, phosphides, troilite and organic polymers occurred through consumption of water's oxygen and release of H₂. Hydration caused formation of serpentine, saponite, chlorite, talc and hydrated salts. Since H₂O was the major reactant in oxidation and hydration, these processes could have been competitive. Redox reactions in asteroids should have been closely connected to hydration (dehydration) during aqueous alteration and thermal metamorphism. For example, dehydration and reduction release H₂O that can be consumed in oxidation and hydration, respectively. We model asteroidal processes in order to quantify the fate of H₂O and water's oxygen in major redox and hydration/dehydration reactions.

Model: Equilibrium compositions in the gas-solid-liquid type closed system O-H-Mg-Ca-Na-K-Fe-Ni-Co-Cr-Mn-Si-Al-C-Cl-S-P were calculated with our codes [4] in ranges of temperature (T , 0-350°C), pressure (P , 0.006-300 bar), water to rock mass ratio (WRR , 10^{-5} - 10^3), porosity and alteration progress, which designates a fraction of rock reacted. Water-free compositions of several H3, LL3, CV3, CM2 and CI chondrites were used to exemplify types of asteroidal rocks. A relative degree of oxidation vs. hydration was quantified as $(\Delta H)/(\Delta OH)^{-1}$, where ΔH represents molar amounts of H in gas and solution and ΔOH stands for the molar quantity of OH and H₂O in minerals.

Results: Water is consumed in different proportions in oxidation and hydration processes. Formation of magnetite usually marks a prevalence of oxidation, except extremely H₂O-deficient cases. Lower T (< ~50-130°C), which also correspond to lower stability of magnetite, favor hydration. At higher T , the degrees of oxidation and hydration do not change much and are often controlled by the magnetite-serpentine assemblage.

Water to rock ratio appears to be an influential parameter that affects degrees of oxidation and hydration. WRR may reflect bulk water content and/or represent a stage of alteration (metamorphism) of a partially reacted rock. In the presence of solution ($WRR > 0.1$ - 0.2), hydration usually dominates except low- P cases (< ~2-10 bar at 100°C). At very low WRR (< 10^{-2} - 10^{-3}), that could be typical for parent bodies of ordinary chondrites, oxidation prevails. At intermediate WRR (10^{-2} - 0.2) without solution, predominant pathways of water consumption are sensitive to WRR and also depend on P . Formation of saponite and other hydrous silicates marks a hydration maximum at lower WRR , and formation of

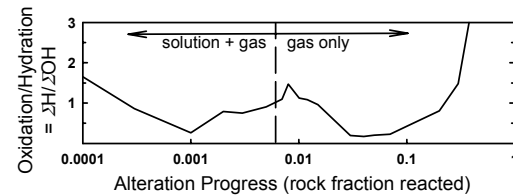


Figure 1. Relative degree of oxidation vs. hydration as a function of alteration progress of the Semarkona LL3.0 ordinary chondrite at bulk WRR of 10^{-3} and original porosity of 0.3 at 100°C.

magnetite signifies an oxidation peak at slightly higher WRR . At $T < \sim 130^\circ\text{C}$, higher P (> 2-10 bar) can suppress formation of magnetite, which favors hydration. At elevated P , degrees of oxidation and hydration do not change much.

As alteration progresses, three peaks of oxidation and two hydration maxima can be observed, especially in H₂O-deficient asteroids (Fig. 1). Early stages of aqueous alteration are characterized by interaction of solution with a very small fraction of rock and cause low- P oxidation of kamacite, phosphides and troilite. Formation of abundant OH-bearing silicates at later stages designates a hydration maximum. Then, formation of magnetite indicates a second oxidation peak. Shortly after consumption of aqueous solution, H₂-rich conditions create potential for reduction of magnetite to ferrous silicates (olivine), while hydrous silicates (saponite) remain stable. At this stage, alteration can be inhibited. If T and/or time permit reactions at the metamorphic stage, both reduction and dehydration occur. Complete dehydration of silicates and preservation of some ferrous silicates designates net prevalence of oxidation at that stage. Note that in H₂O-rich CM/CI type bodies, alteration did not reach an advanced metamorphic stage. Results also show that higher porosity favors oxidation due to lower P . In addition, H₂ escape in a porous medium must have driven further oxidation.

In summary, low P and high T favor oxidation, and high P and low T support hydration. As the alteration progresses, the fate of water's O in redox and hydration/dehydration reactions is unsteadily affected by changing temperature, pressure, porosity, and an amount of reacted rock.

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References: [1] Zolensky M. E. and McSween H. Y. (1988) In *Meteorites and the Early Solar System*, 114-144, U. Ariz. Press. [2] Brearley A. J. and Jones R. H. (1998) In *Planetary Materials, Rev. Mineral.*, 36, 1-398. [3] Keil K. (2000) *Planet. Space Sci.*, 48, 887-903. [4] Mironenko M. V. and Zolotov M. Yu. (2005) *LPS XXXVI*, abstract #2207.