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MELT CONDENSATION FOR THE ORIGIN OF CHONDRULES IN ORDINARY CHONDRITES INFERRED FROM BULK CHEMICAL COMPOSITION AND MASS-DEPENDENT OXYGEN ISOTOPIC FRACTIONATION.

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Introduction: Although chondrule formation by melting of precursor materials has been favored, the model has a fundamental disadvantage that the diversities of bulk compositions are not well explained (e.g. [1]).

Key question: A precise and comprehensive study of chondrule compositions for primitive ordinary chondrites revealed the refractory element abundances being constant and less than the solar value, while a large Mg/Si fractionation exists on both higher and lower sides than the solar ratio, which could not be inheritance from the precursors but is explained by kinetic condensation of silicate melt in dust enriched systems [2]. Another important observation is that the oxygen isotopic composition for chondrules from ordinary chondrites are mass-dependently fractionated, where type I chondrules are lighter with wide variation, whereas type IIs are heavier with a limited range [3]. It has already been known that all metallic elements do not show notable mass-dependent isotopic fractionation, and therefore, oxygen is the only element that shows mass dependent isotopic fractionation. Questions arises are which process is responsible for and which conditions are necessary to generate the chemical and isotopic characteristics of chondrules.

Model: The model by [2, 4] was modified to investigate the conditions where chemical diversity of bulk compositions with oxygen isotopic variations for type I and II chondrules are formed through evaporation and condensation of melt droplets.

Result and discussion: Mass-dependent isotopic fractionation is the direct evidence for the role of evaporation / condensation in the formation of chondrules. Type I chondrules are explained by rapid condensation of silicate melt from the gas with the solar compositions with dust enrichment by more than about hundred. The presence of more oxygen in the gas than metallic elements formed chondrules with light oxygen compositions. The oxygen isotopic variation among type I chondrules was caused by rapid chemical isolation of chondrules from the residual gas. The fairly low Mg/Si composition and homogeneous and heavier oxygen isotopic compositions of type II chondrules are explained by condensation of residual gas to melt droplets after type I chondrule isolation, which kept chemical and isotopic equilibrium during condensation to lower temperatures, and which eventually got volatile components with almost the solar ratios.

COMPLEX EXPOSURE HISTORY OF VACA MUERTA MESOSIDERITE INFERRED FROM NOBLE GASES.
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Introduction: Vaca Muerta is classified as a mesosiderite, which suggests collision event(s) between differentiated asteroidal bodies for its formation. Several compositionally different clasts are found in the meteorite. Sm-Nd ages of 4.4-4.5 Ga [1] and $^{39}$Ar-$^{40}$Ar ages of 3.8-4.0 Ga [2] have been reported. Cosmic-ray exposure age determined for metal phase is 133 Ma [3].

Experimental: Bulk sample (0.2086 g) and chips (0.4844 and 0.4829 g) from a eucritic pebble in the Vaca Muerta mesosiderite were measured for noble gases with stepwise heating method: 8 and 13 temperature steps from 400 to 1800°C. Concentration of $^{81}$Kr and cosmogenic Kr isotopic composition were also determined for a chip (0.2129 g) from the eucritic pebble.

Result and discussion: Ar isotopic ratios at low temperatures are plotted close to the atmospheric value in a plot of $^{40}$Ar/$^{36}$Ar vs. $^{38}$Ar/$^{36}$Ar. At the middle temperatures, however, the ratios plot in a narrow area ($^{38}$Ar/$^{36}$Ar=1.53 and $^{40}$Ar/$^{36}$Ar=87), then go downward to cosmogenic Ar ($^{38}$Ar/$^{36}$Ar=1.54 and $^{40}$Ar/$^{36}$Ar~0). The Ar component (hereafter VM-component) at the middle temperature range must be a mixing product between radiogenic $^{40}$Ar and cosmogenic Ar. Bulk sample shows clear excess in $^{40}$Ar compared with the VM-component, which would be an in situ produced radiogenic $^{40}$Ar after formation of the VM-component. The observed Ar isotopic feature can be explained as: 1) noble gases had been well degassed from differentiated parent bodies prior to a collision, 2) collision of the differentiated asteroids produced the mesosiderite breccia at 4.4-4.5 Ga [1], 3) cosmogenic and radiogenic Ar accumulated in the breccia were mixed at the thermal event which reset K-Ar system (4 Ga determined by $^{39}$Ar-$^{40}$Ar method [2]), and 4) cosmic-ray irradiation during the transit from a Vaca Muerta parent body to the Earth.

Based on the above described model, the transit time is calculated as about 30 m.y., while the period of cosmic-ray exposure at the breccia formation (4.4-4.5 Ga) must be longer than 90 m.y. $^{81}$Kr-Kr exposure age of 180 m.y. for the eucritic pebble is calculated from radiogenic $^{40}$Ar concentration for the bulk sample. Noticeable amount of excess $^{129}$Xe from $^{129}$I could not detected in the samples, which indicates that volatile degassing occurred or continued until the $^{129}$I extinction in the mesosiderite parent body.

Asuka 881020 is the first CH chondrite found in the Japanese Antarctic meteorite collection [1]. It consists mainly of CH chondrite host and minor amounts of phyllosilicate-rich clasts [1]. The host is a mixed material of chondrules, fragmented mineral aggregates (~80%) and FeNi metallic grains (~20%). The chondrules are mostly crypto-crystalline or glassy type and range in size typically from 50 to 100 μm but occasionally up to 200 μm. Overall mineralogical signatures of the host are similar to other CH chondrites [e.g., 2, 3]. Oxygen isotope analysis was performed on twenty four chondrules using an ion probe Cameca 6f at Kyushu University. The results show that oxygen compositions of most chondrules distribute along but slightly (~5 permil in δ17O) above the CCAM line in a range from -10 to +5 permil in δ17O: the range of compositions is similar to chondrules in other carbonaceous chondrites.

The phyllosilicate clasts occupy ~3% of the whole areas of the meteorite investigated. The size of the clasts is variable from 20 to 500 μm across. Pyrrhotite plates and magnetite framoids commonly occur in the clasts. Dolomite crystals with size from 20 to 80 μm are also contained. Synchrotron X-ray diffraction analysis of several clasts indicates that dominant phyllosilicates vary between clasts: one is rich in serpentine and the other is rich in saponite. In both serpentine- and saponite-rich clasts, prism reflections, which are resulted from stacking disorder of tetrahedron sheets, are clearly observed. Major element compositions of phyllosilicate-rich portions in the clasts were obtained using an analytical TEM. In the (Si+Al)-Mg-Fe ternary diagram, compositions of a serpentine-rich clast are plotted between serpentine and low-Ca pyroxene solid solution, while those of a saponite-rich clast are clustered between saponite and low-Ca pyroxene solid solution. The differences in both mineral and chemical compositions between serpentine- and saponite-rich clasts suggest that they are alteration products formed under different physico-chemical conditions. The two types of hydrous clasts were incorporated during/after formation of the CH chondrite parent body. The preservation of serpentine indicates that the temperature during formation of this meteorite has never exceeded 600°C.

ESTIMATION OF SHOCK PRESSURE EXPERIENCED BY EACH ORDINARY CHONDRITE WITH AN X-RAY DIFFRACTION METHOD.
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Introduction: Shock metamorphism is pervasively recognized in meteorites, and it is an important subject to estimate the degree of shock experienced by each meteorite. Chondrites have been classified into six degrees based on the intensity of shock that was recorded as shock textures on olivine [1]. However, the classification is qualitative one in order to know shock pressures.

It is experimentally suggested that the crystal lattice of olivine has been strained by shock and the maximum strain estimated by an X-ray diffraction method linearly increases with the increase of the pressure loaded on it [2]. In this study, we determined apparent strains of olivines in ordinary chondrites by an X-ray method and try to draw the relation line between the maximum strain and shock pressure applicable to ordinary chondrites.

Experimental method: We analyzed eight ordinary chondrites, showing variable degrees of shock. The polished thin sections of the eight chondrites were observed under a microscope and shock stages for each chondrite were determined referred to [1]. Four to eight olivine grains of about 50μm in size, being confirmed to be homogeneous in their chemical compositions, were taken out of the polished thin sections. Their X-ray powder diffraction patterns were obtained by a Gandolfi camera. The position and the integral breadth of each X-ray reflection were precisely determined by applying a profile-fitting technique with a pseudo-Voigt type shape function. The maximum strains of olivine crystals were determined based on the equation, \( \beta = 4e\tan \theta \), where \( e \), \( \beta \) and \( \theta \) are the maximum strain, the broadening due to the strain and the half of the angle between incident and diffraction beams, respectively [3]. The maximum strain \( e \) is equal to \( \Delta d/d \), where \( \Delta d \) is the maximum deviation of the interplanar spacing \( d \) due to distortion of a crystal.

Results and discussion: The maximum strains of olivine crystals for each chondrite are obtained as follows: 0.033-0.044% for Great Bend (S1), 0.037-0.064% for Y-790752 (S2), 0.040-0.092% for Mulga(north) (S2), 0.061-0.108% for Leedey (S3), 0.083-0.122% for Dhurmsala (S3), 0.098-0.160% for Ohuma (S3), 0.107-0.170% for Arcadia (S3) and 0.136-0.190% for Bruderheim (S4). The maximum strains for each chondrite vary by about 0.01% for Great Bend (S1), by about 0.03% for Y-790752 (S2) and by about 0.06% for others. The variation may reflect inhomogeneous stress on each olivine when the chondrite was shocked due to a heterogeneous petrographic texture of a chondrite. Then, the maximum values of the maximum strains for each chondrite are taken as a measure of shock pressure. The maximum strain of olivine is experimentally found to increase linearly with shock pressure [2] and also nonlinearly with shock duration time. Then, the relationship between the maximum strain and shock pressure applicable to chondrites was estimated from the shock-pressure ranges for each shock stage of [1]. The result was also compared to experimentally determined ones of different shock duration time.

SEARCH FOR EXTINCT 36-CL IN ALLENDE CAIs: THE PINK ANGEL.
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Introduction: Radioactive $^{36}Cl$ ($T_\text{½} = 0.3 \text{ Ma}$) has long been suspected to have been present in the Early Solar System. Its actual detection, however, has proven to be difficult. Part of the problem is that Cl-rich phases such as sodalite tend to be alteration rather than primary phases and that the decay of $^{36}Cl$ primarily leads to volatile $^{36}Ar$. Search for $^{36}Ar$ excesses due to decay of extinct $^{36}Cl$ in sodalite-rich CAIs from the Allende meteorite (e.g., [1,2]) have been negative, while a reported excess in bulk Efremovka [3] has shown to be an analytical artifact [4].

Decay to $^{36}S$: Although only 1.9% of decays lead to $^{36}S$, search in S may be advantageous because of the much lower volatility as compared to Ar [5]. Lin et al. [5] found $^{36}S$ excesses correlating with Cl/S in sodalites from a CAI in Ningqiang, corresponding to $^{36}Cl/^{35}Cl \sim 5 \times 10^{-6}$ at the time of sodalite formation. A similar ratio was found in sodalites in the Allende Pink Angel by [6]. On the other hand, we found no evidence for extinct $^{36}Cl$ in our study of another fine-grained Allende CAI [7].

New measurements: Using the Mainz NanoSIMS we performed measurements on a thin section of the Pink Angel kindly supplied by G.J. Wasserburg in order to confirm the results of [6]. Procedures were as described in [7], but there was a problematic background that required subtraction of 90% of the signal at $^{36}S$, much more severe than in [7], where the correction typically amounted to some 30%.

Results: Our results basically confirm the observations of [6] in that $^{36}S$ is enhanced. A weighted fit to our data yields $(^{36}Cl/^{35}Cl)_0 = (4.2 \pm 1.4) \times 10^{-6}$, compatible with the initial $^{36}Cl/^{35}Cl \sim 4 \times 10^{-6}$ of [6]. However, because of the background problem, our errors are somewhat large and it is possible that we deal, in fact, with a disturbed system.

Discussion: A late irradiation origin for $^{36}Cl$ has been favored by [6], similar to the case of $^{10}Be$. However, unlike the latter, which appears to be present in roughly equal abundance in all studied CAIs, $^{36}Cl$ appears to be variable. Critical in the interpretation is when and where the alteration processes occurred that led, among others, to the formation of sodalite [8]. Absence of sodalite from the matrix of their sample has been interpreted by [6] as indication that alteration happened in the nebula rather than on the Allende parent body. We have, however, observed sodalites in Allende matrix, and sodalites have been found in the matrix of many CV3 meteorites [8]. Clearly the possibility of multiple alteration episodes needs to be considered.


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NOBLE GASES IN THE ISHEYEVO METEORITE.
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Introduction: The recently discovered metal-rich carbonaceous chondrite Isheyevo [1] consists of at least two lithologies: a fine-grained, metal-poor (<20vol%) lithology (CH-like) and a coarse-grained, metal-rich (~70vol%) lithology (CB₂-like) [2]. Isheyevo should provide a clue for the genetic relationship between CB and CH chondrites. Here, we report results of stepwise noble gas analyses of Isheyevo meteorite samples.

Results and discussion: The trapped \(^{36}\text{Ar} / ^{132}\text{Xe}\) ratio (~900) is higher than that of Q gases, suggesting that Isheyevo has Ar-rich gases and/or solar noble gases. Isotopic ratios of He and Ne show that Isheyevo contains solar and cosmogenic noble gases. This suggests that Isheyevo is a regolith breccia. The solar \(^{4}\text{He} / ^{20}\text{Ne}\) ratio is about 252, which is comparable to the typical value for solar wind implanted species (258, lunar soil ilmenites 12001, [3]). The trapped \(^{26}\text{Ne} / ^{36}\text{Ar}\) ratio (8.2) is lower than that for lunar soil ilmenites 12001 (26.8, [3]). If solar \(^{26}\text{Ne}\) is lost, solar \(^{4}\text{He}\) would be lost even more. The solar \(^{4}\text{He} / ^{20}\text{Ne}\) ratio is expected to be lower. It is likely that the low \(^{26}\text{Ne} / ^{36}\text{Ar}\) ratio is due to enrichment of trapped \(^{36}\text{Ar}\), i.e., Ar-rich gases. Such Ar-rich gases also have been seen in CH and CB chondrites [4, 5].

Xe isotopic ratios show that the dominant component is Xe-Q, while minor components are cosmogenic Xe and atmospheric Xe in the lowest temperature fraction (600°C). Solar Xe can not be clearly observed. Kr isotopic ratios show the presence of cosmogenic Kr as well as a hint of neutron-induced Kr from Br. The presence of neutron-induced Kr suggests that the preatmospheric size of Isheyevo is larger than 22 cm in radius [6], assuming that the neutron-induced Kr was produced during exposure of the meteoroid.

Cosmogenic \(^{21}\text{Ne}\) concentrations vary from sample to sample. The shortest possible cosmic-ray exposure age is 45Ma, which is calculated from the lowest cosmogenic \(^{21}\text{Ne}\) concentration, the production rate given by [7], the bulk chemical composition and the assumption that the meteorite was exposed to cosmic rays with 4π geometry and with average shielding. The estimated exposure age is comparable to our previous result (~36Ma, [2]).

Assuming that measured \(^{40}\text{Ar}\) is totally radiogenic in origin, the gas retention age is calculated as 4.4Ga from concentrations of K (45ppm) and \(^{40}\text{Ar}\) (3.2×10^4cm^3/g). The estimated gas retention age is longer than our Ar-Ar dating results of <3.5Ga [2], which may result from different degrees of partial loss of radiogenic \(^{40}\text{Ar}\).

ORDINARY CHONDRITES: AN IRON ISOTOPE STUDY.
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Introduction: The properties of iron - its abundance, relative volatility, sensitivity to redox conditions, and occurrence as metal, sulphide and silicate phases - make it an important element to study in ordinary chondrites. High-precision Fe-isotope analyses have only become possible within the past decade due to advances in multi-collector plasma-source mass-spectrometry. Previous studies [e.g. 1, 2, 3] have focused on differentiated meteorites and carbonaceous chondrites, with only a handful of ordinary chondrite analyses yet reported. This is the first extensive study of Fe-isotope fractionations in ordinary chondrites, including analyses of bulk meteorite, chondrules, matrix, metal, and sulphide phases.

Method: Polished blocks of bulk chondrites were analysed by SEM prior to micro-drilling (accurate to <100µm). A wide range of chondrules, chondrule rims, metal, sulphides and matrix samples were extracted, digested and processed by anion-exchange columns. The Fe solutions were then analysed by MC-ICP-MS, with a precision (2σ) of ± 0.06‰ on δ56Fe; see [4] for details of MC-ICP-MS technique. Results are reported relative to the IRMM-14 standard. The same procedures, excluding SEM and micro-drilling, were performed for whole-rock analyses.

Samples: To date, the sample set comprises 16 ordinary chondrites, representing H, L and LL groups, from petrologic type 3.4 to 6. Analyses of more highly-unequilibrated (<3.4) ordinary chondrite samples are pending. A similarly extensive study of carbonaceous and enstatite chondrites is also underway.

Results: The range in Fe-isotope compositions of bulk samples is -0.18‰ to +0.01‰. H, L and LL samples plot throughout this range, though there is a slight bias towards isotopically lighter LL samples. Metal phases range from -0.24‰ up to +0.3‰; low-Ni metal tends to be heavier, with only high-Ni metal found to be isotopically lighter than the standard. Sulphide phases have been found to be isotopically light, ranging from 0 to -0.37‰. Chondrules in Type 3 chondrites exhibit a wide range of compositions, from -0.28‰ to +0.26‰. Some chondrules in Type 4-6 chondrites have equally large fractionations, but on average are less fractionated than in Type 3.

Analyses of almost 100 mineral-separates and bulk samples have revealed a wide and complex range of Fe-isotope compositions in ordinary chondrites. Relationships with other chemical and mineralogical features provide constraints on the processes (evaporative losses etc.) controlling Fe distribution.

CLUES TO CHICXULUB DEPOSITIONAL HISTORY FROM Mg AND K SIGNATURES IN THE YAX-I IMPACTITES.

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Introduction: The ICDP Yaxcopoil-1 drill core, in the annular trough of the Chicxulub crater, exhibits layered impactites consisting of upper suevite and lower impact melt breccia [1]. Impactites are Mg-, and possibly K-rich in certain units [2, 3, this work]. Models that explain these Mg and K signature signatures can be divided into two categories: (1) Chicxulub impactites are the result of a silicate melt later altered by some kind of fluid [3, 4], or (2) impactites were initially Mg-, and/or K-rich from primary melt composition [2, 5], or some combination thereof. Each model has substantial implications for the dynamics of impactite deposition, and hydrothermal processes.

Methods and Results: Microprobe and X-ray diffraction analyses were conducted to determine textural and chemical relationships of melt clasts, the origin of Mg and K signature, and if the impactites contain hydrothermal minerals. We found the K and Mg signatures are spatially decoupled. In the melt breccias, K-enrichment exists only on angular, silicate melt clast rims, while the matrix material consists of a separate Mg-, calcite- rich phase with no K-enrichment. The upper suevite also contains these two phases: A Mg-, calcite rich phase, and a Si-, Al-, sometimes K- rich phase, but both phases comprise the groundmass and schlieren melt clasts. The results of this study support a sequence as follows: (1) Dolomite and granite were melted and ejected during transient crater formation. (2) Granitic melt was quenched, brecciated, and enriched in potassium by seawater. (3) Transport and deposition followed, the nature of which was somewhat different for melts at depth than from those above. At depth, the granitic melt was rapidly permeated by Mg- rich dolomitic melt immediately before or upon deposition, during the lateral surge associated with the collapse of the transient crater. Above, starting at Unit 3 [1], dolomite and granite melt textures appear to be consistent with simultaneous ballistic transport, and the two melts were likely in contact longer. Lower in the section, melts were then deposited as melt breccia, consisting of angular silicate melt clasts and dolomitic melt matrix, while melts above were deposited as suevite, consisting of schlieren dolomite and silicate melts. This study found no evidence for extensive hydrothermal alteration at the Yax-1 site, although silicate melt in upper suevite does appear to have been altered by dolomite melt, and possibly seawater.


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IN SITU IDENTIFICATION OF A PRESOLAR SIC X GRAIN, PRESOLAR SILICATES AND 13C-RICH GRAINS IN THE ALLAN HILLS 77307 METEORITE.


Introduction: Presolar grains have traditionally been identified by the measurement of single grains from acid residues or size-separated matrix grains [1]. Whereas the analysis of these samples allows for more isolated studies of specific mineral phases or grain sizes, the analysis of polished meteorite sections is well-suited for surveying the relative abundances of different presolar phases in a sample that has undergone less laboratory processing, and for investigating petrologic relations (if any) between presolar grains and surrounding meteoritic materials.

Raster ion imaging in the NanoSIMS ion microprobe has been employed in the identification of very small isotopically anomalous silicate grains in IDPs [2, 3], meteorites [4, 5], and micrometeorites [6]. Exploiting the enhanced capabilities of the new Carnegie NanoSIMS 50L, we analyzed a polished section of the CO3.0 meteorite ALHA 77307 by simultaneous ion imaging of the O and Si isotopes. For some areas, we imaged the O and C isotopes, as well as 28Si. With this experimental setup, anomalous silicates, oxides, SiC, and C-rich grains can be identified.

Results: We measured a total area of ~2700 μm² and identified 13 presolar silicate grains, all of which are smaller than 300 nm. Most of these grains have O isotopic compositions consistent with Group 1 presolar oxides [7], but 2 of the silicate grains fall into Group 3 and one grain is a Group 4. The Si isotopic compositions of 5 of these grains were determined, and fall in the range seen for mainstream SiC grains and other presolar silicate grains [5, 8]. We also identified a <200 nm grain having depletions in both 29Si and 30Si (δ29Si= -280±54, δ30Si= -387±61), similar to those typically seen in SiC X grains originating from Type II supernova. The NanoSIMS 28Si/16O ratio of this grain is high relative to the surrounding matrix grains, most of which are silicates, suggesting that it is indeed a SiC. The abundance of SiC X grains in bulk meteorite samples is only ~100 ppb, compared to ~110 ppm for presolar silicate grains. The detection of this grain demonstrates that even very rare presolar grain types can effectively be identified with the experimental technique employed. We plan to measure the C and N isotopic compositions of this grain.

Two grains having slight enrichments in 13C (δ13C= 67±5; 78±8) were also identified. SEM-EDX analyses (5kV) of these grains show peaks for C and O. It is possible that these grains are organic in nature. We will measure the N and H isotopes in the NanoSIMS to more fully characterize these grains.

AN EXPERIMENTAL STUDY OF THALLIUM PARTITIONING AND ISOTOPE FRACTIONATION DURING PLANETARY CORE FORMATION PROCESSES
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In a recent study [1] it was proposed on the basis of thallium (Tl) isotope variations in iron meteorites that the short-lived radioactive nuclide $^{205}$Pb, which decays to $^{205}$Tl with a half-life of 15 Myrs, was present in the early solar system. A caveat of the $^{205}$Pb-$^{205}$Tl decay system is that Tl only has two isotopes ($^{203}$Tl and $^{205}$Tl) and it is therefore difficult to distinguish between Tl isotope variations from the decay of $^{205}$Pb and stable isotope fractionation. Specifically, it was concluded that the troilite nodules of iron meteorites contain Tl that is isotopically fractionated relative to the metal phase. These are therefore not suitable as indicators of $^{205}$Pb decay.

Modeling of terrestrial accretion and core formation furthermore implies that either the Earth’s core is highly enriched in Tl compared to iron meteorites or most of the original terrestrial Tl budget was lost to space, for example during the putative Moon-forming giant impact. The latter is mechanistically difficult. The partitioning behavior of Tl between metal, silicate and sulfide is, however, unknown. It is therefore currently not possible to predict the amount of Tl present in the core and compare it with that required by isotopic mass balance modeling.

In order to investigate the behavior of Tl during core formation and crystallization processes, we experimentally reacted mixtures of silicate, sulfide and metal in a piston-cylinder apparatus at 2 GPa and 1750°C. Preliminary results on Tl partitioning between liquid metal and silicate indicate a $D_{\text{metal/sil}} < 1$, which would result in a silicate Earth with a much higher Tl concentration than is observed today. As Tl is relatively chalcophile, it is not surprising that $D_{\text{metal/sil}}$ is dependent on the sulfur concentration of the liquid metal, whereby the highest partition coefficients are observed for pure liquid sulfide ($D_{\text{metal/sil}} > 150$). However, the partition coefficient for Tl at a sulfur concentration similar to that of the Earth’s core (about 1.7%, [2]) is still too low to extract sufficient Tl from the silicate mantle.

An alternative mechanism for placing additional Tl in the core is offered by the late addition of pure sulfide, a process recently revisited by Wood and Halliday [3]. If the $D_{\text{metal/sil}}$ value determined here is representative for sulfide segregation from the mantle, then <0.8% (by weight) of the mantle would have to precipitate as sulfide in order to balance the Tl budget of the bulk Earth. This does not appear unrealistic, as the giant impact would have contributed a significant amount of sulfur to the Earth [3].

Additional experiments will be performed to determine if any Tl isotope fractionation occurs during core formation or crystallization and to obtain more detailed information on the Tl partitioning during metal-sulfide-silicate segregation.

THERMOLUMINESCENCE STUDY IN THE JAPANESE ANTARCTIC METEORITES COLLECTION: ASUKA ORDINARY CHONDRITES

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Introduction: Induced TL (thermoluminescence), the response of a luminescent phosphor to a laboratory dose of radiation, reflects the mineralogy and structure of the phosphor, and provides valuable information on the metamorphic and thermal history of meteorites. Especially the sensitivity of the induced TL is used to determine petrologic subtype of unequilibrated ordinary chondrites [1]. Natural TL, the luminescence of a sample that has received no irradiation in the laboratory, reflects the thermal history of the meteorite in space and on Earth. Natural TL data thus provide insights into such topics as the orbits of meteoroids, the effects of shock heating, and the terrestrial history of meteorites [2]. Natural TL properties also can be applied to find paired fragments [3].

Primitive ordinary chondrites: We measured induced and natural TL properties of ninety Asuka unequilibrated ordinary chondrites (LL: 16, L: 27, H: 47) from Japanese Antarctic meteorite collection from D1, D2, and D3 sites near the Sør Rondane Mountains. Most of the chondrites had TL sensitivities over 0.1, corresponding to petrologic subtype 3.5-3.9. Six chondrites, A-881244 (L3), A-87319 (L3), A-881607 (LL3), A-881328 (LL3), A-9043 (L3), and A-881408 (LL3) were revealed to be primitive ordinary chondrites under petrologic subtype 3.2. They are particularly significant in understanding the nature of primitive material in the solar system.

Pairing: Natural and induced TL properties were also applied to find paired fragments, and we found 26 TL potential paired fragments, 9 groups in the Asuka samples [4,5]. A group of H3 at D1 site comprises a chain of paired fragments. A H3 chondrite might be shower near the Sør Rondane Mountains. We will determine terrestrial ages for ten chondrites by cosmic produced nuclides, 14C and 10Be, and we will get information not only for assurance of TL pairing but also for glaciological setting near the Sør Rondane Mountains.

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3D-RAINAN SPECTROSCOPY OF THE PDFS IN QUARTZ FROM THE RIES IMPACT STRUCTURE. H. Nishido1, A. Gucskić, K. Ninagawa1, and T. Okumura1, 1Okayama University of Science, Dept. of Applied Physics, Ridai-cho 1-1, Okayama, 700-0005, Japan, 2University of West Hungary, Bajcsy-Zs. u. 4., Sopron, H-9400, Hungary. E-mail: ciklamensopron@yahoo.com

Introduction: The study of Raman properties of unshocked and experimentally shock-deformed minerals (e.g., quartz) has the potential to provide a tool that can be used in shock barometry, to supplement the methods available so far (mainly optical microscopy; also birefringence and density measurements of shocked quartz are rarely done; cf. [1]). Micro-Raman spectroscopy is by now a fairly routine technique that is not too complicated in its use (unlike, e.g., the NMR technique of [2]), and the identification of a Raman spectroscopic method that would allow to a) identify shocked minerals, and b) give information on the shock pressure would be useful for the identification and study of impact structures.

Experimental Procedure: Raman spectra were obtained with an Almega: confocal micro-Raman spectrometer with a 20 mW at 532 nm with Nd:YAG laser excitation system.

Results and Discussion: Raman spectra of quartz have been described in great details by previous scientists, e.g., [1]. They found changes in frequency and line-width of the 206 and 464 cm\(^{-1}\) \(A_1\) Raman modes of quartz, which were determined over temperatures from 23 to 800°C and simultaneously at pressures between 0.1 MPa and 2.1 GPa, using a hydrothermal diamond-anvil cell (HDAC). The positions and widths of peaks in the Raman spectra of our measurements are in good agreement with these previous studies. Raman spectra of the coesite as a high-pressure polymorph of quartz have been reported by e.g., [2]. On the other hand, in laser-heated diamond cell experiments, found that coesite exhibits three relatively strong Raman bands at 489, 552, and 790 cm\(^{-1}\) and stishovite shows a strong peak at 790 cm\(^{-1}\) [3]. These authors concluded that stishovite was converted to coesite at 10 GPa and 2330 °C. Raman spectra of Planar Deformation Features (PDFs) in the shocked quartz from the Ries impact structure exhibit a pronounced peak at around 455 cm\(^{-1}\), which can be assigned to Si-O stretching vibration, whereas typical low-quartz has a sharp and intense peak at 464 cm\(^{-1}\). This frequency shift might be related to a distortion of structural configuration caused by shock-metamorphism. 3D Raman imaging analysis using this Raman peak reveals a striped image comprised of high and low crystalline parts. This 3D Raman image corresponds to the optical image of PDFs. Consequently, Raman spectroscopy is a potentially useful tool that can be used to characterize PDFs (as most important mineralogical criteria of presence of shock metamorphism) of quartz from impactites. These results also give new insight into the structural changes that occur in quartz during shock metamorphism, and the pressures associated with these changes.

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CONSTRAINING THE NUMBER OF LUNAR AND MARTIAN METEORITE FALLS.

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Introduction: Extensive searches in Antarctica and in other arid environments for extraterrestrial materials are increasing the number of lunar and Martian meteorites to our collections. However, in many instances, the meteorite is paired with other fragments from the same object that impacted Earth. Identification of these pairs is a critical component of the studies of source objects, impact events, and orbital dynamics of those meteorites. Chemical and petrographic properties are useful criteria for distinguishing individual falls for both lunar and Martian meteorites, however this information alone is not always sufficient for all objects, especially lunar meteorites. Cosmogenic nuclide studies of lunar and Martian meteorites have contributed significantly to our understanding of these objects. The specific goals of these measurements are to constrain or set limits on the following shielding or exposure parameters: (1) the depth of the sample at the time of ejection from the Moon or Mars; (2) the transition time from ejection off the lunar or Martian surface until capture by the earth; (3) and the terrestrial residence time. The ejection age in conjunction with the sample depth on the Moon or Mars can then be used to model impact and ejection mechanisms. We have measured cosmogenic nuclides in 48 (33 individual) lunar and 37 (30) Martian meteorites; a summary of new measurements is presented below.

New Measurements: Although the data are still preliminary, we measured cosmogenic nuclides in 10 new lunar and 7 new Martian meteorites since our last report [1].

Lunar meteorites. Among 11 Dhofar meteorites we studied, we found 7 individual falls. Dhofar 489/908/911/1085 are paired. Our measurements indicate that they were ejected from >1,100 g/cm² on the Moon and the transition time from Moon to Earth is 4±1 kyr; the terrestrial age is ~300 kyr. Dhofar 081/280/910 are paired and were ejected from a depth of 200-230 g/cm² on the lunar surface. The preliminary ¹⁰Be ⁴π exposure age of Dhofar 1084 is 0.32±0.06 Myr. We identified 6-7 individual falls of NWA meteorites using cosmogenic nuclide. ¹⁰Be and ²⁶Al results indicate: (1) NWA 3160 is possibly paired with NWA 773; (2) NWA 2200 and 3136 were ejected from a depth of 50-100 g/cm² on the lunar surface; (3) NWA 3163 was ejected from a depth of 300-320 g/cm². The ¹⁰Be ⁴π exposure age of NEA 001 is 0.44±0.08 Myr. Conclusive exposure histories will be obtained after ³⁶Cl and ⁴¹Ca measurements.

Martian meteorites. New exposure ages of shergottites are consistent with previously identified exposure age clusters. The preliminary ¹⁰Be exposure age of NWA 1195, 2046, and 2626 are 1.1±0.2 Myr. The exposure ages of NWA 1068, 1110, 1460, 2646, 3171, and GRV 99027 are in the range of 2.5-3.1 Myr. ³⁶Cl and ⁴¹Ca terrestrial age measurements are in progress.


CORRELATED MICROANALYSIS OF PRESOLAR MATERIALS.


Introduction: Presolar grains and organic matter in extraterrestrial materials are samples of stars and molecular clouds available for study in terrestrial laboratories [1-3]. As such, they provide new insights, not obtainable by other means, into a wide variety of astrophysical processes and environments. However maximizing the information obtained requires correlated multi-analytical techniques on the same samples. Fortunately, the explosion of nanoscience in recent years has led to the development of many new techniques enabling high-sensitivity, multi-technique analysis of micro-scale materials.

Presolar Grains: Presolar grains are tiny (2 nm to 20 μm) pristine samples of stardust preserved in meteorites and interplanetary dust particles (IDPs) [1]. Their isotopic compositions are used to determine stellar sources (e.g., red giant, supernova) and to constrain stellar evolution and nucleosynthesis models. Their microstructures (e.g. crystal structure, defects, etc) provide insights into the physical and chemical conditions of grain condensation in stars and dust processing in the interstellar medium [4, 5]. Ideally, a complete picture of a presolar grain includes both multi-element isotopic data and microstructural data, but obtaining correlated data on the same grains has been difficult due to the necessity of thin (~100 nm) samples for structural studies and thicker samples for isotopic measurements. The development of high sensitivity, high spatial resolution secondary ion mass spectrometry (NanoSIMS) and focused-ion-beam (FIB) sample preparation has greatly enabled combined isotope-structural presolar grain studies. For example, correlated sub-micron isotopic and structural data for individual graphite and SiC grains from supernovae [6-8] provide an unprecedented view of dust condensation within supernovae.

Presolar Organic Matter: Both meteorites and IDPs contain organic matter with H and N isotopic signatures indicating an origin in interstellar space prior to solar system formation [2, 3]. The organics are not well characterized, especially at micro-scales, and correlated analyses are essential for maximizing the yield of information. Using SIMS isotopic measurements to identify isotopically anomalous materials, traditional ultramicrotomy and/or FIB techniques can be used to extract samples for additional analyses by, e.g., transmission electron microscopy, synchrotron x-ray and infrared spectroscopy, and micro-Raman analysis [9-11]. Such correlated analyses have indicated both some common features of primitive organic matter and strong variations on small spatial scales, indicating a diversity of formation processes and subsequent evolution.

EXTREME $^{13}$C AND $^{15}$N ENRICHMENTS IN A MURCHISON PRESOLAR SiC GRAIN.


Although the stellar sources for most presolar SiC grains are well established, the origin of grains with extreme $^{13}$C, $^{15}$N and $^{30}$Si excesses is controversial. Originally attributed to novae [1], isotopic data for some of these grains are better explained by supernovae [2]. We report isotopic data for presolar SiC grains from Murchison, one of which has the largest $^{13}$C and $^{15}$N excesses yet measured in presolar grains.

We used the ims-6f ion probe to automatically analyze C and Si isotopes in 1550 0.5-5 μm SiC grains from a new residue prepared using the CsF technique [3]. The Si data are shown in the Figure. The abundances of sub-groups are in the ranges of previous studies, with the exception of the supernova-derived X grains, which are present at 2x higher abundance than previously observed. Since X grains are apparently more disordered than other SiC grains [4], the higher abundance might indicate that they preferentially survive the CsF chemistry, relative to the standard HF/HCl treatment. Two highly unusual grains were also identified. Grain 505-1 has solar $^{28}$Si/$^{30}$Si, a huge $^{30}$Si excess ($^{30}$Si=850‰) and light C ($^{12}$C/$^{13}$C=150). Grain 240-1 has excesses in both $^{28}$Si and $^{30}$Si, but lies to the right of the mainstream correlation line, and has $^{12}$C/$^{13}$C=1.04±0.01. A preliminary measurement with the new Carnegie NanoSIMS 50L indicates $^{14}$N/$^{15}$N=5 for this 800 nm grain. SEM-EDX analysis indicates a very high Al concentration (>10 wt%) and we estimate [N]=2 wt% from the NanoSIMS CN/C ratio.

Both the $^{12}$C/$^{13}$C and $^{14}$N/$^{15}$N ratios of grain 240-1 are lower than previously reported for any presolar grain and are consistent with pure nova ejecta with white dwarf masses of ~1.0-1.2 M [5]. A supernova origin is unlikely since the non-explosive H burning in such stars cannot produce such low $^{12}$C/$^{13}$C. Grain 505-1 is similar to a previously-reported grain, M26a-454-3 [3]. Its $^{13}$C depletion rules out a nova origin. Additional NanoSIMS isotopic measurements (e.g., Al-Mg, Ti, Ca) for both unusual grains will help unravel their origins.

TRAPPING NOBLE GASES IN FULLERENES.
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Introduction: The possible role of natural fullerenes as a carrier of planetary noble gases is under debate. Research on synthetic fullerenes, such as produced by carbon-arc evaporation and soot deposition, suggests that the encapsulation of the noble gases in C60 and C70 is proportional to the partial pressure of the gas at the time of fullerene formation (1,2).

Experiments: Graphitic Smokes (GS) are made by electrically heating a 5 cm-long graphite rod thinned to increase its electrical resistance. For each experiment the graphite rod was heated quickly to produce a ‘hot cylinder’ of carbon vapor in a pre-mixed noble gas atmosphere. The condensed smoke formed a deposit on an aluminum plate positioned in the condensation chamber 15.2 cm above the continuously heated graphite rod. This thin graphite rod allows carbon to condense more uniformly in comparison to the arc-discharge evaporation process typically used in fullerene synthesis (4,5).

Kimura et al. (6) used the arc-discharge technique for the preferential production of higher fullerenes that were also produced by Rotundi et al. (5) wherein soot contained higher fullerenes (4). The arc-discharge process is non-linear in comparison to the simple evaporative heating method (3) that we have adapted for our studies of synthetic noble gas carbon carriers. Previous investigations of the bulk GS sample that was analyzed for Xe yielded values as high as 13.7 x 10^6 cm3 STP/gm of 132Xe (3). This value is ~ 2 orders of magnitude greater than typical 132Xe amounts for other synthetic carbon residues (7). While this result was exciting, the origin of the carrier for GS bulk material remained unknown. We obtained GS soot material synthesized in a noble gas mixture of 49% Ne, 49% Ar, 1% Xe and 1% Kr with the balance provided from He for a 300-torr atmosphere maintained during GS soot condensation (3).

For previous fullerene investigations (8-10) we developed a two-step extraction method for isolating fullerenes from natural samples: first, Toluene extraction that separated predominately C60, C70 up to C100, and a second extraction with high boiling solvent (1,2,4 trichlorobenzene or 1,2,3,5 tetramethylbenzene) to separate higher fullerenes in the C100 to C300 range. We will report the results of these studies at the meeting.

INITIAL ISOTOPIC HETEROGENEITIES IN ZAGAMI:
EVIDENCE OF A COMPLEX MAGMATIC HISTORY.
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Introduction: Interpretations of Zagami’s magmatic history
range from complex [1,2] to relatively simple [3]. Discordant
radiometric ages led to a suggestion that the ages had been reset
[4]. In an attempt to identify the mechanism, Rb-Sr isochrons
were individually determined for both fine-grained and coarse-
grained Zagami [5]. Ages of ~180 Ma were obtained from both
lithologies, but the initial 87Sr/86Sr (I0) of the fine-grained lithol-
yogy was higher by 8.6±0.4 \( \epsilon \)-units. Recently, a much older age
of ~4 Ga has been advocated [6]. Here, we extend our earlier in-
vestigation [5].

Rb-Sr Data: In [5] we applied identical, simplified, proce-
dures to both lithologies to test whether a grain-size dependent
process such as thermally-driven subsolidus isotopic reequilibra-
tion had caused age-resetting. Minerals were separated only by
density. In the present experiment, purer mineral separates were
analysed with improved techniques. Combined Rb-Sr results give
ages (T) = 166±12 Ma and 177±9 Ma and I0 = 0.72174±9 and
0.72227±7 for the coarse-grained and fine-grained lithologies,
respectively. \( I_{0f} \) in the fine-grained sample is thus higher than in
the coarse-grained sample by 7.3±1.6 \( \epsilon \)-units. The results for the
coarse-grained lithology are in close agreement with T = 166± 6
Ma, \( I_{0c} = 0.72157±8 \) for an adjacent sample [7] and T = 178±4
Ma, \( I_{0c} = 0.72151±5 \) [4, adjusted] for a separate sample. Thus,
fine-grained Zagami appears on average to be less typical of the
bulk than coarse-grained Zagami.

Conclusions: Fine-grained Zagami was suggested to have
inherited more numerous pyroxene cores from an earlier magma
chamber than coarse-grained Zagami [1]. Higher \( I_{0f} \) in the finer-
grained parts may in part be inherited from radiogenic Sr from
old pyroxenes in the magma reservoir. However, most LIL ele-
ments in Zagami probably were derived from a crustal reservoir.
Thus, higher \( I_{0f} \) in the finer-grained lithology also could have
come from a greater contribution from an old, crustal, high Rb/Sr
component. Failure to achieve isotopic equilibrium throughout
the magma suggests rapid, complex, magmatic processes, per-
haps initiated by sudden injection of a metasomatic fluid. Vari-
tions in the initial abundance of pyroxene cores plus early crys-
tallization of pyroxene may have caused the magma to “choke”,
freezing isotopic differences into different volumes. These ef-
fects probably affected most of the ~175 Ma shergottites contrib-
uting to ambiguities in interpreting their isotopic data.

References:
MICROCHONDRULES WITHIN A TROILITE-RICH RIM AROUND A CHONDRULE IN YAMATO 790448 LL3 CHONDRITE.

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Introduction: In ordinary chondrite many small spherical silicates have been recognized [1-3]. Silicate spherules with <40um diameter were arbitrarily defined as “microchondrules,” compared to normal sized chondrules that are larger than several hundred micrometers. Microchondrules have been found in FeO-rich matrices or chondrule rims so far. Here we report the presence of microchondrules in a sulfide-silicate-metal rich rim surrounding a chondrule in Yamato (Y) 790448 LL3.2 [4] chondrite.

Methods: Polished thin sections prepared from Y790448 were investigated with an optical microscope and a SEM. Chemical compositions were determined with an EMPA.

Results and Discussion: A POP chondrule (800um in diameter) in Y790448 has a rim (up to 150um in thickness) consisting of troilite, silicates and metal. Pyroxene and olivine compositions of the chondrule are typically Fs16 and Fa 20, respectively. The silicates in the rim consist dominantly of low-Ca pyroxene. There are two kinds of morphology for the pyroxene: round (microchondrules with 5-25um in diameter) and fragmental (irregular and blade-like). The fragmental pyroxenes, probably chondrule fragments, show chemical zoning: at a point 3um inside from the edge of pyroxene fragments the composition is slightly enriched in FeO (Fs 20) compared to the further inner part (Fs 16). In contrast, chemical compositions of pyroxene microchondrules are homogeneous within each of them and moderately higher in FeO (up to Fs 25) than those in the enclosed host chondrule.

Troilite and Fe-Ni metal fill clacks in the microchondrules and the interstices between pyroxene fragments and microchondrules, which suggests that opaque minerals have been melted. The Co content in kamacite in the rim is in the range of those in chondrules and matrix in Bishunpur [5]. This is unlike S-rich chondrule rims where Co enrichments were observed and thought to result from oxidation and sulfuration with the nebular gas [6]. Thus, the kamacite composition in the sulfide-silicate-metal rich rim in Y790448 implies that heating occurred in an environment separated from nebular gas, i.e., in the parent body. If we assume that both of the pyroxene fragments and microchondrules have formed from the host chondrule pyroxenes, their FeO variations could be due to different duration and/or peak temperature of the heating event. Such heterogeneous heating effects might be caused by impact shock in the parent body.

CATHODOLUMINESCENCE AND RAMAN SPECTROSCOPIC CHARACTERIZATION OF SHOCKED QUARTZ FROM THE BARRINGER AND RIES IMPACT CRATERS

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Introduction: We discuss an effect of shock-metamorphism on quartz from impact craters by means of cathodoluminescence (CL) and 3D Raman spectrometry. Cathodoluminescence microscopic and spectroscopic methods are useful techniques, which enable easily characterization of planar microstructure in quartz [1-3]. Micro-Raman spectroscopy is a technique that provides information on lattice vibration from microscopic area.

Samples and Methods: The samples employed here are twenty quartz grains at various shock stages from impact craters; Ries Crater and Barringer Meteor Crater. They were prepared as polished thin sections using nonluminescent epoxy resin and coated with 20 nm thickness carbon. The planar microstructures (PDFs: Planar Deformation Features and PF: Planar Fractures) were observed in several quartz grains under a petrographic microscope. Raman spectra were obtained with a confocal micro-Raman spectrometer at 20 mW on Nd:YAG laser (532 nm) excitation system. CL spectral measurements were carried out using a SEM-CL (SEM combined with a grating monochromator) with an accelerating voltage of 15 kV. The sample temperature was controlled in the range from –192 to 25 °C using a cryostage.

Results and Discussion: Raman spectra of shocked quartz exhibit a pronounced peak at around 455 cm\textsuperscript{-1}, which can be assigned to Si-O stretching vibration, whereas typical low-quartz has a sharp and intense peak at 464 cm\textsuperscript{-1}. This frequency shift might be related to a distortion of structural configuration caused by shock-metamorphism. 3D Raman imaging analysis using this Raman peak reveals a stripe pattern suggesting lamination layer comprised of high and low crystalline parts. This 3D Raman image corresponds to the optical image of PDFs. Furthermore, SEM-CL imaging of some shocked quartz gives apparent features related to PDFs, which can be clearly observed under polarized microscope.

CL spectra of shocked quartz exhibit a doublet peak in the range from 450 to 500 nm. Upon heating the CL intensity rapidly decreased. The decay of CL intensity in low-quartz is well known as a temperature quenching effect. Activation energy in temperature quenching process was evaluated by assuming Mott-Seitz model. Arrhenius plot leads to activation energy (E) of 0.068 ~ 0.085 eV in the range from –180 to –30 °C for shocked quartz. On the other hand, unshocked ordinary quartz exhibits two temperature quenching processes, where the E is 0.03 eV up to –110 °C and 0.235 eV above –110 °C. Therefore, the effect of shocked-metamorphism might affect to electronic transition process in defect centers correlated to CL emission.

IDENTIFICATION OF M1 AND M2 SITES IN OLIVINE AND PYROXENE BY MÖSSBAUER SPECTROSCOPY OF ORDINARY CHONDRITES

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Introduction: It is well known that both olivine and pyroxene contain two crystallographically nonequivalent octahedral sites M1 and M2. These sites are occupied by Fe^{2+} and Mg^{2+} ions. The contrast of M1 and M2 sites geometry in olivine is less than that in pyroxene. The Fe–Mg distribution between two sites is of interest due to its possible application for minerals cooling history determination. Mössbauer spectroscopy was successfully used to distinguish M1 and M2 sites in pure synthetic and natural olivines, orthopyroxenes and clinopyroxenes [1–4]. Ordinary chondrite is a mixture of olivine, pyroxene, troilite, metal and iron oxides. Therefore, its Mössbauer spectra contain superposition of several components that increases difficulties to distinguish subspectra corresponded to M1 and M2 sites in. In this work we demonstrate the possibility to reveal sites M1 and M2 for olivine and pyroxene in ordinary chondrites using Mössbauer spectroscopy with high velocity resolution.

Methods: Samples of ordinary chondrites Farmington L5 (1), Kunashak L6 (2), Vengerovo H5 (3) and Zvonkove H6 (4) were prepared as a powder. All samples were measured at room temperature using high stable and sensitive Mössbauer spectrometer SM-2201 in transmission geometry with moving absorber. Mössbauer spectra were measured with registration in 4096 channels with further presentation in 1024 channels by summation of neighbor channels.

Results: Mössbauer spectra of ordinary chondrites were fitted using 7 or 8 components including 4 components related to M1 and M2 sites in olivine and pyroxene. Some results are given in the Table. Higher values of quadrupole splitting were related to higher octahedral site distortion.

<table>
<thead>
<tr>
<th>Sample</th>
<th>M1</th>
<th>M2</th>
<th>M1/M2 area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>δ, mm/s</td>
<td>ΔE_Q, mm/s</td>
<td>δ, mm/s</td>
</tr>
<tr>
<td>Olivine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.207</td>
<td>2.982</td>
<td>1.119</td>
</tr>
<tr>
<td>2</td>
<td>1.195</td>
<td>3.023</td>
<td>1.162</td>
</tr>
<tr>
<td>3</td>
<td>1.209</td>
<td>2.986</td>
<td>1.133</td>
</tr>
<tr>
<td>4</td>
<td>1.209</td>
<td>3.000</td>
<td>1.131</td>
</tr>
<tr>
<td>Pyroxene</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.256</td>
<td>2.672</td>
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<td>2</td>
<td>1.221</td>
<td>2.485</td>
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<tr>
<td>3</td>
<td>1.202</td>
<td>2.540</td>
<td>1.169</td>
</tr>
<tr>
<td>4</td>
<td>1.212</td>
<td>2.576</td>
<td>1.177</td>
</tr>
</tbody>
</table>

Experimental error is ±0.014 mm/s

Conclusion: Using Mössbauer spectroscopy with high velocity resolution the M1 and M2 sites in olivine and pyroxene of ordinary chondrites were identified and compared with [1–4].

STUDY OF CH/CB METEORITE ISHEEVO BY MÖSSBAUER SPECTROSCOPY

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Introduction: Carbonaceous chondrites CH and CB enriched with Fe(Ni,Co,Cr) metal phases are the most primitive meteorites. The meteorite bencubbinite Isheevo was recently found in Russia. This unique meteorite contains zones with different lithology [1]. Metal grains in these zones had the same size (0.1–0.3 mm) and similar structural variety. Meteorites of CR clan were not studied by Mössbauer spectroscopy yet. Therefore, in this work the first study of bencubbinite Isheevo by Mössbauer spectroscopy was made.

Methods: Two samples of surface and internal regions of meteorite Isheevo fragment were prepared as powders. Samples were measured at room temperature using high stable and sensitive Mössbauer spectrometer SM-2201 in transmission geometry with moving absorber. Mössbauer spectra were measured with registration in 4096 channels with further presentation in 1024 channels by summation of neighbor channels.

Results: Mössbauer spectra of Isheevo samples of surface and internal regions (Fig. 1) consisted of the main asymmetrical sextet and several minor components. Asymmetrical sextets in both samples were better fitted as superposition of 4 sextets: 1 – $\alpha$-Fe(Ni) ($H_{eff}$=346 kOe), 2 – $\alpha$-Fe(Ni) ($H_{eff}$=334 kOe), 3 – $\alpha$-Fe(Ni) ($H_{eff}$=333 kOe), and 4 – $\gamma$-FeNi ($H_{eff}$=312–314 kOe). Other spectral components were different for the samples of external and internal regions. In case of external region (Fig. 1, a) two different models with the same $\chi^2$ values were used. Small quantities of olivine (5), pyroxene (6) and unknown high spin ferrous compound (7) were the same in both models. The first model showed the presence of two singlets parameters of which were close to taenite $\gamma$-Fe(Ni) and niningerite (see [2]) while the second model supposed the presence of ~9 % ferric oxide which subspectrum represented by one doublet (8) like in ordinary chondrites [3]. In the spectrum of internal region (Fig. 1, b) small quantities of olivine (5), unknown high spin ferrous compound (6) and ~3 % ferric oxide (7) were found.

Fig. 1. Mössbauer spectra of meteorite Isheevo surface (a) and internal regions (b). 1–8 are the spectral components. T=295 K.

Conclusion: The first Mössbauer study of CH/CB meteorite Isheevo revealed several metal phases and different minor components in external and internal regions. However, further study by various techniques is required for clarification.

REFRACTORY LITHOPHILE ELEMENT FRACTIONATION IN ISHEYEVO SILICATES

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Introduction: We have conducted a LA-ICPMS study of refractory lithophile elements (RLEs) in order to trace high-T gas/solid fractionation in Isheyevo silicates (chondrules & CAIs).

Results: REEs are largely unfractonated in cryptocrystalline, metal-poor and -rich chondrules with <1–7 CI, resembling those in other metal-rich chondrite chondrules [1]. One exception (IV, metal-rich PO chondrule) shows distinct ultrarefractory REEs [2]. Three of 6 CAIs show volatility-controlled group-II REE patterns [3] with the remaining 3 having largely unfractonated REEs. Isheyevo chondrules define Y/Ho = 24, which is close to the solar ratio of 26.2±0.4 [4]. Chondrule IV has an Y/Ho-ratio of only 10.4; opposite to what is expected for an object enriched in the ultrarefractory component [4]. This suggests that REEs in IV may have condensed after removal of the very first condensates with high Y/Ho. Two of 3 CAIs with group-II patterns have subchondritic Y/Ho (7 & 11). Isheyevo chondrules have Zr/Hf = 36, which is close to the chondritic value of 34.3±0.3 [5]. Only IV deviates from that ratio with Zr/Hf = 46, which we relate to fractional condensation (i.e. \(T_c(Zr) > T_c(Hf)\)) [6]. CAIs show variable Zr/Hf with those CAIs with chondritic Y/Ho also having chondritic Zr/Hf. Nb/Ta shows a larger scatter than Y/Ho and Zr/Hf with an average ratio of 18 in Isheyevo chondrules, which is similar to the chondritic value of 19.9±0.6 [5]. Chondrule IV has Nb/Ta = 9 that is explained by \(T_c(Ta) > T_c(Nb)\) [6]. Nb/Ta in CAIs varies from 12.2 to 24.5.

Discussion: Unfractonated REEs suggest formation of the majority of Isheyevo chondrules from primitive material i.e. that has not undergone major nebular or parent body chemical factionation. The same conclusion is drawn from near chondritic Y/Ho, Zr/Hf- and Nb/Ta-ratios. Chondrule IV shows evidence for incorporation of an ultrarefractory component that formed by high-T fractional condensation. Fractionated Y/Ho in IV suggests effective isolation of dust at the high-T end of condensation sequence. Volatility-controlled REEs that are known from other carbonaceous [7-11] and ordinary chondrite [12] chondrules are interpreted by incorporation of CAI-like material into chondrule IV. CAIs in Isheyevo have REE patterns that are well known for decades from carbonaceous chondrite CAIs [3] and are explained in term of volatility-controlled chemical factionation in an H-rich nebular gas [13]. Our data are not supportive for an origin of Isheyevo chondrules different from chondrules of other chondrites, i.e. though a late impact [14].

THE CHONDRITE PARADOX

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One of the most perplexing aspects of primitive chondritic meteorites is the narrow range and solar-like bulk chemical and isotopic composition of cm sized samples in contrast to the large compositional variations of their individual mg sized components: chondrules, inclusions, fragments, matrix.

Chondrules in ordinary chondrites (OC) and in carbonaceous chondrites (CC) show a wide range of chemical compositions, including variable degrees of oxidation and a large range of oxygen isotope ratios of individual chondrules, e.g. [1]. Components of primitive chondrites are in apparent thermodynamic disequilibrium with each other. Curiously we assume that the stronger the disequilibrium, the more primitive is the meteorite. A simple nebular model would predict the opposite. The chaotic mixture of chondrules, fragments, metal and matrix accreted to a meteorite with a very simple bulk composition, when scaled to average solar system abundances. The Na/Mn ratio is solar in bulk OC and CC chondrites [2], OC even have solar Na/Mg ratios. The Na/Mn ratio varies widely among individual chondrules, fractionates strongly during evaporation and condensation and is extremely redox sensitive.

The source of the material of the inner solar system is the extremely well mixed interstellar matter (ISM). New results on Os [3] and Zr [4] isotopes demonstrate that physically separable nucleosynthetic components are present in chondritic meteorites, excluding total evaporation, isotopic homogenisation and condensation of matter at the beginning of the solar system. Uniform isotopic composition of solar system material is achieved by sampling the extremely well mixed ISM, which produces on melting, evaporation and condensation coarse grained chondrule precursors. Random sampling of these components leads to the observed uniform and solar like bulk meteorite compositions.

Accretion of chondrites occurred from chemically fractionated materials homogeneously distributed in the nebula on a very local scale. A large compositional stratification and gross deviations from the solar like average chemistry of the nebula can be excluded, except for a general depletion of volatiles. Fragments from destroyed differentiated planetesimals of earlier generations [5] do not contribute to chondritic bulk compositions. Compositional similarities of the Earth and CV-chondrites suggest a huge CV-like reservoir and small OC-reservoirs [6].

AR-AR AGE OF SHERGOTTITE DHOFAR 378: FORMATION OR EARLY SHOCK EVENT?

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Introduction: Martian shergottite Dhofar 378 (Dho378) is from Oman, weighs 15 g, and possesses a black fusion crust [1]. The plagioclase in other shergottites has been converted to maskelelite by shock, but Dho378 experienced even more intense shock heating, estimated at 55-75 GPa [2]. Dho378 plagioclase (~43 modal %) melted, partially flowed and vesiculated, and then partially recrystallized [3]. Here we report 39Ar-40Ar dating of K-enriched phases of Dho378. We suggest that the determined age may date the intense shock heating event this meteorite experienced, but not the later impact that initiated the CRE age.

Ar-Ar Results: The 39Ar-40Ar data for 16 stepwise temperature extractions of mixed mesostasis plus plagioclase show the following major characteristics. Changes in the K/Ca ratio and in the differential rate of 39Ar release with extraction temperature suggest three distinct, but overlapping Ar diffusion domains: <13%, 13-45%, and >45% cumulative 39Ar release. The youngest Ar-Ar age, ~162-165 Myr is observed at ~28-40% 39Ar release, which we attribute primarily to the mesostasis. Extractions releasing >45% 39Ar, probably from plagioclase, suggest older Ar-Ar ages and indicate release of trapped martian 40Ar. An isochron plot for 8 extractions, releasing 3-45% of the 39Ar and corrected for 36Ar using directly measured 36Ar, gives an Ar-Ar age of 143±4 Myr (where the ± ignores the uncertainty in applying a correction for 36Ar). Applying a correction assuming only one-half of the measured 36Ar gives an age of 159±2 Myr. Correcting for cos36Ar using the minimum measured 36Ar gives a minimum possible age of 138±5 Myr. All of these ages are within combined uncertainties of the Sm-Nd age of 157±24 Myr [4]. The trapped 40Ar/36Ar ratio obtained from the isochron is largely defined by the highest [K] data.

Conclusion: We suggest that the ~143 Myr Ar-Ar age determined from the Dho378 isochron may not date the impact that ejected the meteorite into space ~3 Myr ago, but a much earlier impact at ~143 Myr. The relationship between the similar Ar-Ar and Sm-Nd ages is not clear. Diffusion data for 39Ar examined in thermal models for post-shock cooling of Dho378 indicate that total loss of 40Ar from the low-temperature phase but only partial loss of trapped 40Ar from the high-T phase are consistent with inferred cooling rates. For the Ar-Ar isochron not to have been reset ~3 Myr ago would seemingly require: 1) the mesostasis was not heated above ~500°C, in spite of the observation that plagioclase was melted; or 2) K-rich phases heated to melting cooled so rapidly, on the order of seconds, such that 40Ar diffusive loss did not occur; or 3) the Ar-Ar age dates only feldspar and not mesostasis, in spite of high (~1) K/Ca ratios observed.

Acknowledgements: We thank H. Takeda for supplying the Dho378 sample, C-Y Shih for separating the plagioclase analyzed, D. Garrison for lab support, and T. Mikouchi, G. McKay, L. Nyquist, and F. Hörz for helpful discussions.

MONOMICT IMPACT BRECCIA FROM DHALA STRUCTURE, ARCHEAN BUNDELKHAND CRATON, CENTRAL INDIA: MACRO- AND MESOSCOPIC IMPACT-INDUCED DEFORMATION.

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Introduction: The Dhala impact structure centered at 25°17'59.7"/ 78°8'3.1", with an estimated diameter of ~15 km is located in the westernmost part of the Bundelkhand craton, Shivpuri District, Madhya Pradesh State, India [1]. The presence of unequivocal and diagnostic shock metamorphic features, extensive macro-deformation, and a large impact melt breccia dyke has already been reported [2]. The Dhala structure has a well defined central uplift surrounded by largely eroded multiple breccia rings. The breccia rings are separated by crater-fill sediments and suevite deposits. Monomict impact breccia outcrops occur as elliptical bodies with maximum elevation of 360 m. The present study reports the data from the field study of monomict granitoid breccia outcrops and IRS-1D (PAN+LISS-III) hybrid geocoded analogue data.

Results: A total of 98 presently exposed breccia outcrops occur around the central uplift with highly variable characteristics. The clasts are very angular, vary in size and show varied orientation. The average aspect ratios of clasts from one outcrop to another vary. Brittle structures (like joints and faults) and melt (±breccia) veins of varied length and width are observed. About 657 joint data and 55 fault trends have been collected from the breccia rings of Dhala structure. The faults show sinistral as well as dextral offset. The study of satellite data reveals the presence of a strong regional E-W fabric on both the northern (“Raksa Shear Zone”; [3]) and the southern (“Bundelkhand Tectonic Zone”; [4]) sides of the crater structure. Radial and concentric fractures are observed in and around the central uplift up to a distance of about 10 km from the center. The central uplift has undergone faulting. The regional E-W trending mylonitic fabric (steeply dipping due N) shows a gentle swerving to the ESE around the Dhala structure. Giant quartz veins with nearly NE-SW trend and relatively lighter appearance in the satellite data are the most conspicuous linear structures with positive relief in the environs of the crater. Mafic intrusives can be identified as linear outcrops with darker appearance and with a NW-SE trend. Quartz veins as well as mafic dykes show offset and fracturing at the outcrop scale, in the vicinity of the Dhala structure. The brittle structures in areas covered by alluvium are basically identified by abruptly (90°) changing stream trends.

Discussion: The distribution and density of brittle structures observed in breccia outcrops are variable. Apparent melt veins at the mm to cm scale in the monomict breccia are oriented parallel to important fracture directions. Joint analysis shows a radial pattern with slight complication due to pre-existing fabric elements (giant quartz veins, mafic dykes and the “Bundelkhand Tectonic Zone”). The presence of brittle structures in giant quartz veins and mafic intrusives and swerving of the mylonitic foliation in diorite suggest that the impact event post-dates these respective events.

MINERAL ASSEMBLAGE IN TARGET ROCKS OF THE ARAGUAINHA IMPACT CRATER AND SHOCK PRESSURE ESTIMATION

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Introduction: The Araguainha impact structure is a well preserved, 40-km-diameter, complex impact crater, situated within the northeastern part of the Parana Basin, straddling the border between Mato Grosso and Goias states, central Brazil. The impact structure has a central uplift of ca. 6 km diameter. This work presents the results of the petrographic study of one-hundred and twenty thin sections from different sampling areas from the NE to the SW across the structure. The rocks affected by the impact include the Precambrian to Ordovician crystalline basement, exposed at the center of the uplifted core, and Permian to Ordovician sedimentary units (Furnas, Ponta Grossa and Aquidauana formations), occurring in ring structures around the central uplift [1].

Petrology: The core of the central uplift consists of a quartz-syenite with cm-sized subhedral K-Feldspar phenocrysts, exhibiting planar deformation features (PDFs) in up to three crystallographic orientations per grain, as well as diaplectic K-feldspar glass. The other main constituents are plagioclase, quartz, amphibole, biotite and accessory minerals (carbonate and zircon). Plagioclase is coarse-grained, subhedral, exhibiting polysynthetic twinning, areas of maskelynite and up to two directions of PDFs. Quartz crystals are fine-grained, anhedral, exhibit undulatory extinction and well-developed, generally decorated PDFs, with up to three directions per grain, as well as planar fractures. Amphibole is medium-grained and subhedral. Biotite is fine-grained and subhedral, and has abundant kink bands, as well as inclusions of zircon that show one or two directions of shock features. Impact melt breccia was sampled at a location close to the center of the structure. It contains subrounded to rounded clasts of medium-grained quartz, coarse-grained K-feldspar and fine-grained muscovite, carbonate and zircon. The matrix has a fluidal texture with finest-grained quartz and K-feldspar microliths, and voids filled by secondary quartz. The texture is indicative of rapid cooling. Sandstone from the Furnas, Ponta Grossa and Aquidauana formations consists of rounded or sub-rounded quartz, plagioclase, K-feldspar, muscovite, biotite, chlorite, epidote, zircon and magnetite. The grain sizes range from medium-grained (quartz, plagioclase and K-feldspar) to fine-grained (muscovite, biotite, chlorite) and very fine-grained (epidote, zircon and magnetite). Sandstones from a radial distance of ca. 5 km from the core only display undulatory extinction and deformation bands in quartz that are not diagnostic shock deformation.

Conclusion: Intense pressure produced during the impact induced characteristic shock metamorphism in the rocks of the central uplift, but not beyond. Planar deformation features in quartz, K-feldspar and plagioclase, and occurrence of diaplectic glass in K-feldspar and plagioclase (maskelynite) indicate that the quartz-syenite of the central uplift experienced shock pressures between 20 and 35 GPa. In the sandstones, however, the absence of characteristic shock effects indicates that the rocks in the outer part of the central uplift through to the outer rim of the structure were affected by pressures of no more than 8 GPa.

HF-W CHRONOMETRY OF AUBRITES
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Introduction: Aubrites are achondrites that formed under highly reducing conditions. They contain different silicate lithologies that formed during igneous processes on the parent body. They also contain small amounts of metal. The depletion of siderophile elements in aubrites indicates segregation of metal in the parent body [1]. The timescales of metal formation and igneous differentiation in the aubrite parent body can be most effectively studied using $^{182}$Hf–$^{182}$W chronometry. Here we present the first Hf-W data for aubrites.

Results: Hf-W data were obtained for metals from Norton County and two silicate-rich fractions from Norton County and Pena Blanca Spring. Analytical methods are similar to those described in [2]. The W concentrations in the two silicate-rich fractions are only a few ppb, reflecting the strong depletion of siderophile elements in aubrites. Metal from Norton County contains ~400 ppb W and has a radiogenic W isotope composition of ~5.5 $\varepsilon_W$ (where $\varepsilon_W$ is the deviation of $^{182}$W/$^{184}$W from the terrestrial standard value in parts per 10,000). The silicate-rich fractions, despite having elevated Hf/W, exhibit W isotope compositions similar to that of the Norton County metal. Owing to the low W content in these silicate-rich fractions, however, their W isotope data have high uncertainties, such that with more precise analyses $\varepsilon_W$ differences between different fractions might eventually become resolvable.

Discussion: The radiogenic W isotope composition of Norton County indicates a high Hf/W in the mantle of the aubrite parent body, consistent with Hf-W fractionation due to metal segregation (i.e., core formation). Additional Hf-W fractionation might have occurred during silicate melting in the mantle. The radiogenic W isotope composition of the Norton County metal requires a late mobilization of radiogenic W from silicates into the metal. Calculating an age for metal formation requires knowledge of Hf/W in the reservoir from which the metal formed. Although this is currently not known, the similarity in W isotope composition of the Norton County metal and silicate-rich fractions suggest that the last W isotope equilibration between metal and silicates occurred late (after a few half-lives of $^{182}$Hf). This is consistent with equilibrated Cr isotopes in Norton County [3] and with relatively young Mn-Cr and I-Xe ages for the aubrite Bishopville [4,5]. Determining precise Hf-W ages for aubrites needs to take into account potential cosmogenic $^{182}$W-production by neutron-capture of $^{181}$Ta during prolonged exposure to cosmic rays. These effects are restricted to silicates and do not affect the W isotope composition of the Ta-free metals, indicating that the elevated $\varepsilon_W$ of the Norton County metal can be interpreted to chronological significance. The similarity of W isotope compositions of metals and silicates in Norton County suggests that cosmogenic $^{182}$W additions in the silicates were small and did not exceed ~3-4 $\varepsilon$ units.

Introduction: Cometary dust exhibit negative branches of polarization of light scattered at small phase angles [1]. This feature gives an opportunity to estimate physical parameters of the dust. To make such estimates one needs to use a light scatter theory for small particles with irregular shapes. There are several methods of light scatter calculations for such particles. One of them is the T-matrix method [2]. Recently we modify the T-matrix method, which allows us to calculate photometric and polarimetric properties of irregularly shaped particles comparable with the light wavelengths very rapidly [3]. This T-matrix modification is now the most prospective for any light scatter calculations, in particular for light scatter studies of celestial bodies, including comets.

Model: The particle shape is presented by an angular dependence of the distance from the particle center to its surface \( r(\theta, \varphi) \). As a model of cometary particles we used particles of a random Gaussian shapes [4]. The cometary particles are suggested to be silicate with the refractive index \( m = 1.6 + 0.005i \).

Results and discussion: Dark points in Fig. 1 present the measured negative polarization branch of light scattered by the Halley comet [1]. Solid line in Fig. 1 presents results of our simulation for the cometary particles calculated with the modified T-matrix method. Model particles were averaged over both orientation and size parameter in a range of \( X = 0.5 \ldots 6.5 \) with the power law of probability density \( \rho = Ar^{-2.4} \), where \( A = 0.546 \) is the normalizing factor. As one can see our calculations reproduce both the depth and inversion angle of the branch and qualitatively describe its shape. The difference at small phase angles could be explained with the influence of another mechanisms of negative polarization, e.g., with the coherent backscatter effect that may contribute to polarization at these phase angles [5].

SEARCH FOR $^{58}$Fe ANOMALIES IN ORGUEIL AND ALLENDE METEORITES.
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Introduction: Iron is the second most abundant element in terrestrial planets after oxygen. Hence, any nucleosynthetic effect revealed by its isotopic composition will likely apply to a large fraction of the matter involved in planet formation. However, with the exception of the early finding of mass-independent $^{58}$Fe variations in three refractory inclusions from the Allende meteorite [1], subsequent searches could not confirm this result [2,3]. The three other stable isotopes of iron, $^{54}$Fe, $^{56}$Fe and $^{57}$Fe, were found to show only mass-dependent isotopic variations [4-6]. Presolar grains might be an exception to this rule [7], although this finding was subsequently challenged [8]. To evaluate whether anomalous abundances of the neutron-rich $^{58}$Fe isotope actually occur in early solar system material, we developed a new analytical approach based on high resolution MC-ICP-MS.

Material and methods: A step-leaching procedure, derived from [9,10], was employed to extract selectively Fe from different mineral fractions of the Orgueil chondrite (from MHN, Toulouse). Chondrules and refractory inclusions were handpicked from a crushed chip of Allende (from USNM, Washington). We developed a high mass resolution MC-ICP-MS protocol involving desolvating nebulization after enhanced Fe purification to measure $\delta^{57}$Fe and $\delta^{58}$Fe with a similar level of precision per amu. The reproducibility estimated so far on $\delta^{58}$Fe is <0.3‰ (2SD).

Results: Leaching solutions from Orgueil show large mass-dependent variations (range: 1.0‰) in $\delta^{58}$Fe, depending on the nature of the phase being dissolved relating to the temperature, length and acid strength of a given leaching step. In contrast, no mass-independent $^{58}$Fe enrichment or depletion could be detected within ±0.1‰. Similarly, Allende components show several permil mass-dependent Fe isotope variations, as previously observed [4, 6], but again, no $^{58}$Fe anomalies have been found yet.

Conclusions: We have been so far unable to reproduce the mass-independent $^{58}$Fe variations found by [1] in the Allende meteorite. This conclusion was previously reached on different material [2,3], though it is based here on high mass resolution MC-ICP-MS analysis. Additional measurements are needed on inclusions of Allende and other meteorites to strengthen this conclusion. If confirmed, this would restrict the inference of an initial mass-independent isotopic heterogeneity of elements, excluding oxygen, to a limited fraction of the matter making up terrestrial planets.

PARTIALLY EQUILIBRATED NITROGEN IN HAMMADAH AL HAMRA 237 METEORITE.
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The Hammadah al Hamra 237 (HaH 237) meteorite contains about 60-70 vol% Fe,Ni-metal [1] [2]. Metal occurs exclusively outside chondrules and often is enclosing silicate inclusions.

A sample of HaH 237 has been studied by stepped combustion [3]. Since the separation of a clean metal phase is very difficult because of the intergrown texture of this meteorite, it is useful to compare data obtained by stepwise pyrolysis with those obtained by combustion.

The metal phase is often combusted before silicates release the bulk of the gases. We added two combustion steps at 750°C and 850°C after the 1000°C pyrolysis step. The results obtained by the two complementary techniques are shown in Figure 1.

The nitrogen signatures in the low-temperature release of both techniques are similar and increase to a maximum close to $\delta^{15}$N = +200‰, which indicates that combustion of the metal phase apparently does not significantly affect the overall signature. Similarly, the later pyrolysis release steps are uniform, suggesting isotopic equilibration. However, the later combustion steps reveal the presence of a lighter nitrogen component, which is duplicated in the added combustion steps of the pyrolysis experiment, indicating the existence of a phase that was only partially equilibrated.

Figure 1. Comparison of nitrogen signatures in HaH 237 obtained by combustion and by pyrolysis. Solid symbols are from this study, open symbols from Sugiura et al. [3]. All circles are $\delta^{15}$N. All squares are normalized N concentrations (ppm per °C). The ▲ symbol is $\delta^{15}$N from combustion, this study, The ▼ symbol is normalized N from combustion, this study.

For some years, we have been studying clusters of craters on Mars. We identified one category of isolated “small clusters” (10m-scale craters spread over few hundred m) that match our predicted parameters for primary stone meteoroids fragmenting in the present Martian atmosphere [1]. We also found scattered “large clusters” (700m-scale craters spread over 5-10 km), which we concluded must be created by breakup of very large secondary blocks (500-m scale) ejected from large (≥10s km) primary craters [2]. We visualize weak (perhaps pre-fractured) blocks breaking up during launch, with fragments spreading at few m/s during ½ hour flight out of atmosphere, through space, and back through the atmosphere. The size-frequency distribution (SFD) of the fragments (and craters in the cluster) has an unusual bell-shape, rather than the “traditional” power law. Ivanov (private communication) has suggested this SFD may fit a Weibel distribution, characteristic of one-time breakup events. Recent work by WKH has found a similar SFD in discrete clusters with rays from crater Gratteri, albeit at smaller scale (80m-scale craters spread over 1 km). This confirms for the first time an observational link (in SFD) between the scattered “large clusters” and clusters known to come impact crater secondary ejecta. Large impacts may launch larger semi-coherent blocks than have been commonly modeled.

NEW I-Xe DATA FOR CHONDRULES FROM THE L4 BJURBÖLE METEORITE.
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I-Xe studies of chondrules sometimes provide more questions than answers. Iodine host phase is difficult to identify when chondrules are small and separation of pure mineral phases is not possible. In these cases the interpretation of I-Xe ages is difficult, since chondrules potentially contain multiple iodine-carrier phases. Nevertheless, age information from different mineral components in chondrules or other complex samples [1] can be successfully resolved if, during step-wise heating, radiogenic xenon from different components is released at different temperatures. Thus, among 43 LL chondrules studied so far, 10 have yielded two well resolved distinct isochrones, with higher temperature releases corresponding to older apparent I-Xe ages. Lower temperature I-Xe ages generally reflect post formation alteration. Not only do LL chondrules tend to be younger with increasing metamorphic grade, but the spread between high- and low-temperature ages increases also, suggesting longer or multiple alteration events for higher metamorphic grade meteorites [2].

A similar trend is observed for H4 NWA267 [3] and H5 Richardson. Our recent study of 3 Elenovka L5 chondrules demonstrates the presence of two distinct iodine carrier phases in one of the samples, with an age difference between the high- and low-temperature phases of 27 ± 10 Ma. I-Xe studies of 2 Saratov L4 chondrules yield ages that differ by 12 Ma [4].

Earlier studies of L4 Bjurböle chondrules [5] provided 13 high precision I-Xe ages without indication of multiple iodine host phases. With the refined absolute normalization of the internal standard Shallowater [6], absolute ages of the Bjurböle chondrules cluster at 4564.8 – 4563.3 Ma, 2.4 Ma after formation of CAI’s, the estimated time of the chondrule formation [7].

A new I-Xe study of 6 other Bjurböle chondrules is under way to explore the possible presence of low-temperature iodine carrier phases. The lower temperature isochrons may have been overlooked since earlier step-wise heating extractions have been done with 200°C incremental temperature steps. The first chondrule yielded relative I-Xe age of 0.0 ± 0.7 Ma. Low temperature peaks on the release profiles of radiogenic 129Xe and 128Xe correspond to the experimental points that form a correlation line of the same slope that the major apparent isochron, but require a different sub-planetary trapped Xe component [8].

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MICROBIAL STRUCTURES IN HYDROTHERMAL DEPOSITS AS BIOMARKERS FOR MARS

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Introduction: Hydrothermal systems may potentially provide microbial habitats on Mars. We have investigated silica sinters with green microbial layers, from Waiotapu, New Zealand in order to characterise the nature of microbial structures that could be used as potential biomarkers. This study will be extended to examine microbial activity in basaltic hydrothermal deposits.

Samples and Methods: The sample was obtained from an extinct sinter deposit 1 m from an acidic (pH 2.6) hot (40-41°C) stream that flows into a crater lake [1]. The textures and mineralogy of the samples were determined using backscattered electron and secondary electron imaging with chemical analyses by energy dispersive spectroscopy.

Results: The host sinter is primarily a fine-grained porous aggregate of aluminous oxyhydroxides and amorphous silica composed of compositionally distinct parallel fibres >10nm across. Pores include sub-micron interfibre spaces within the fine-grained matrix to larger (>100 μm) irregular voids resulting in a variable porosity.

A variety of irregular clasts (<21 μm - 1.5 mm in size) are present within the host sinter and comprise ~50 vol% of the samples. Lithic and crystal clasts are the most abundant and are dominated by irregular silica grains showing zoning, with subordinate clasts of partially altered potassic feldspathic glass. Clasts of feldspathic glass are banded and exhibit preferential dissolution of certain bands and deposition of amorphous silica. Rare zircon grains are also present.

Pore spaces and cracks consisting of highly porous (>70 vol %) botryoidal threadworks of amorphous silica are also observed. Threadworks consist of sub-parallel, interlinked sheets of amorphous silica (<2.6 μm thick). Botryoidal overgrowths of amorphous silica occur often only on one side of the silica sheets but sometimes between them suggesting this was a fluid pathway. Areas of threadwork having no clear truncated margins, that may have formed insitu, are observed in the fine-grained matrix. In a few areas, sinuous layers of titanium oxide (<2 μm in width) were observed coating the silica sheets.

The green layer within the sinter differs primarily from the surrounding matrix in its high concentration of spherical meshwork structures, possibly indentations of spinose plant spores [2]. Highly eroded silica filaments may represent preserved micro-organisms.

Discussion: Threadwork structures observed in the sinters are most abundant within and in proximity to the inferred microbial layer and may have formed by microbial deposition; however, an inorganic origin through the dissolution of silica is also possible. The presence of titanium oxide layers within the silica threadworks, however, is significant since HFSE are highly insoluble. Mobilisation of Ti³⁺ by microbial action may, therefore, have occurred and provide an easily identifiable biomarker.

HIGH PRECISION W ISOTOPE MEASUREMENTS OF IRON METEORITES
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The $^{182}$Hf-$^{182}$W system ($t_{1/2} \approx 8.9$ Myr) is very useful for dating metal-silicate differentiation in the parent bodies of iron meteorites relative to the beginning of the solar system (with initial $\varepsilon^{182}$W of $-3.47 \pm 0.20$ defined by a CAI isochron [1]). Accurate age determinations may help us better constrain accretion and differentiation timescales, planetesimal sizes, and possible heat sources. Cosmogenic effects have been documented for W isotopes, which may limit the usefulness of this chronometer for dating early solar system processes [2-4]. Indeed, the variations measured in $\varepsilon^{182}$W cannot be totally ascribed to the decay of $^{182}$Hf. A major challenge is to find a proper way to correct for these effects. In preliminary work, we reported resolvable deficits in $\varepsilon^{184}$W for two iron meteorites with high exposure ages (Tlacotpec, IVB and Deep Springs, Ungrouped) [5, 6]. We report here new high precision W measurements of a larger set of iron meteorites from groups IAB, IIAB, IIIA, IVAB and IID.

$\varepsilon^{182}$W. All the magmatic iron meteorites with low exposure ages show a narrow range of $\varepsilon^{182}$W, from $-3.35\pm0.06$ to $-3.58\pm0.05$, indicating that metal-silicate segregation was contemporaneous or slightly postdated the formation of CAIs (within $\pm 2$ Myr). The non-magmatic iron meteorite BoHumilitz (IA) has more radiogenic $\varepsilon^{182}$W of $-3.02\pm0.09$. Except for Skookum (IVB), iron meteorites with long exposure ages all show deficits in $\varepsilon^{182}$W ($-3.77\pm0.04$ to $-4.25\pm0.05$) relative to the inferred initial solar system value. This most likely resulted from exposure to cosmic radiation, a conclusion that agrees with recent studies [4, 7-8].

$\varepsilon^{184}$W. Except for IVB iron meteorites and Deep Springs, all other samples have values indistinguishable from the NIST standard. All IVBs, with both low and high exposure ages, show similar depletions ($\sim -0.1 \varepsilon$) in $\varepsilon^{184}$W. This cannot be explained by cosmic irradiation because one would expect to see a correlation with $\varepsilon^{182}$W. It may instead be the imprint of nucleosynthetic effects as has been observed for Mo and Ru isotopes [9-11]. At this stage, no correction of cosmogenic effects on $\varepsilon^{182}$W can be made based on $\varepsilon^{184}$W measurements.

METAMORPHIC HISTORY OF PRISTINE CHONDRITES
AS REVEALED BY ORGANIC MATTER: A NEW
PETROLOGIC CLASSIFICATION

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A new approach for determining the degree of metamorphism of pristine chondrites has been recently successfully applied to series of unequilibrated Ordinary (OCs), carbonaceous CV and CO chondrites [1-3]. Its principle is that the structure of Organic Matter (OM) trapped in the matrix is irreversibly transformed by thermal metamorphism, and thus reflects the metamorphic grade. This transformation is independent from the mineralogical context and aqueous alteration. Thus it does not suffer from artifacts and is valid whatever the chondrite chemical class. OM maturity is provided through Raman spectroscopy [4]. We present here a synthesis of extended measurements collected on ~40 chondrites, and we discuss further the interpretation of OM maturity in terms of thermal history as well as several implications.

We suggest that OM maturity, as derived from Raman spectroscopy, reflects the temperature of the metamorphism peak (TMP). For the most metamorphosed chondrites (PT>3.7), a geothermometer calibrated using terrestrial rocks may even be used [5]. A TMP of 330 ± 30 °C is estimated for Allende (CV3), consistently with earlier independent mineralogical indicators [e.g. 6]. The petrologic types derived from this approach thus exhibit an unambiguous signification, and allow comparison of objects belonging to different chemical classes. Another advance is the high sensitivity of this approach to weak metamorphism grades. In particular, the results show that Semarkona (LL3.0) cannot be further considered as the metamorphism onset as it experienced some metamorphism. Unfortunately, Raman spectroscopy is not sensitive to very weak metamorphic grade, and the actual metamorphism onset has not been determined. Some antarctic chondrites were found to exhibit some metamorphism grade ranging between Semarkona and type 3.1 as Bishunpur and Krymka, but no objects were found ranging between type 1/2 (CM/CI/CR) and Semarkona. For this reason, we propose to establish a new petrologic scale using the FWHM-D Raman parameter normalized to Semarkona. In such a framework, Semarkona’s PT is 1, all objects investigated in our study do have a PT > 1, and the actual metamorphism onset is equal to 0 (but practically speaking it is not accurately located). For the most metamorphosed objects, a temperature of metamorphism peak is provided along with PT. Furthermore, aqueous alteration should be considered as an independent geological process, characterized by another scale, as objects may have experienced high degrees of both metamorphism and aqueous alteration [2].

We would recommend this approach for classifying objects in collections. The technique is fast, easy to implement, can be performed on raw rocks and Raman micro-probes are a widespread analytical tool.

Nickel Isotopes in Angrites: Chronological Interpretation vs. Nucleosynthetic Anomalies? G. Quitté¹, M. Bizzarro², A. Markowski¹ and C. Latkoczy³. ¹IGMR, ETH Zurich, Switzerland. E-mail: quitte@erdw.ethz.ch. ²Geological Inst., Univ. of Copenhagen, Denmark. ³Lab. for Inorganic Chemistry, ETH Zurich, Switzerland.

Introduction: Angrites are rapidly cooled differentiated meteorites that formed very early in the solar system history [1,2]. Angrites are thus critical samples when trying to inter-calibrate different chronometers. Al-Mg and Pb-Pb ages for Sahara 99555 have been recently determined, and the measurements of W [3-4] and Ni isotopes are currently underway to broaden the number of chronometers used on this meteorite. Sahara 99555 is of particular interest because of its pristine nature, which may suggest that the Fe-Ni system remained undisturbed, even if Ni is very sensitive to metamorphism. ⁶⁰Fe decays to ⁶⁰Ni with a short half-life of 1.49 Myr, and this chronometer can thus be used to precisely date planetary accretion and evolution. Moreover, Ni isotopes can provide strong constraints on the nucleosynthetic events that occurred shortly before the start of the solar system. All Ni isotopes are indeed produced by a statistical equilibrium process (e-process), but ⁶²Ni and ⁶⁴Ni are preferentially produced in a neutron rich environment (e- or r-process), whereas an excess of ⁶¹Ni reflects a major contribution from an s-process.

Analytical procedure: Mineral separates and whole rock samples for Sahara 99555 have been analyzed in two different laboratories and results have been compared and combined. In both cases, Ni has been separated from the matrix elements using ion exchange procedures. At ETH Zurich, an additional liquid-liquid extraction has been performed. The Ni isotopic composition has been determined using a MC-ICPMS (Axiom in Copenhagen and the new large geometry and high resolution Nu1700 in Zurich).

Results and Discussion: Whole rock samples and mineral separates display a range of Fe/Ni ratios varying from ~ 1500 to ~ 11000. When normalizing the isotope data to the ⁶⁰Ni/⁵⁸Ni ratio, only one pyroxene fraction with elevated Fe/Ni ratio shows a resolvable ⁶⁰Ni-excess of 87 ± 30 ppm, although a broad correlation between ⁶⁰Ni/⁵⁸Ni and the Fe/Ni ratio is observed when combining all fractions. The slope of this regression corresponds to a ⁶⁰Fe/⁶⁰Ni of ~ 2*10⁻⁹. If we interpret this line as an isochron, Sahara 99555 seems to have formed >10 Myrs after CAIs, which is inconsistent with results obtained from absolute and other short-lived chronometers. Furthermore, the intercept of this regression is identical to the terrestrial standard, which is inconsistent with late re-equilibration of the Fe-Ni systematics. When normalizing the isotope data to the ⁶¹Ni/⁵⁸Ni ratio, we note the presence of ⁶²Ni-deficits ranging from 30 to 100 ppm in some of the samples, and no resolvable excesses in ⁶⁰Ni. This discrepancy may be attributed to the presence of variable nucleosynthetic effects on the normalizing isotopes (⁶⁰Ni and ⁶²Ni) and/or large uncertainties associated with the measurements of the ⁶⁰Ni/⁵⁸Ni ratio. It is not clear from these preliminary results whether or not resolvable ⁶⁰Ni, ⁶²Ni or ⁶⁴Ni anomalies are present in these fractions. More replicate measurements and analysis of other fractions are underway.

CORRELATED EXCESSES OF $^{60}$Ni AND $^{62}$Ni IN REFRACtORY INCLUSIONS.

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Introduction: Calcium aluminium rich inclusions (CAIs) – considered to be the first objects that formed in the solar system – commonly show nucleosynthetic heterogeneities. The origin of these anomalies may be linked to the production of the short-lived nuclides that were also present in the early solar system. Short-lived nuclides can be generated by irradiation and spallation during an active phase of the young sun or by nucleosynthetic events in stellar environments. The determination of their initial abundances thus enables one to test different models. Iron-60 decays to $^{60}$Ni ($t_{1/2} = 1.5$ Myr) and is of particular interest because it cannot be produced locally in the solar system by irradiation.

Technique and Results: We analyzed six CAIs from Alindle and one CAI from Efremovka. Nickel has been extracted from the sample with a three step chemical procedure. Following a first ion exchange, a liquid-liquid extraction was performed. The Ni fraction was further purified on a second ion exchange resin. The Ni isotopic composition has been measured using a high resolution MC-ICPMS (Nu 1700 instrument) at a mass resolution of 2600. The external reproducibility for a standard is about 0.3 and 0.6 for the $^{60}$Ni/$^{58}$Ni and $^{61}$Ni/$^{58}$Ni ratios respectively. Each sample has been measured up to 13 times in different sessions. Most CAIs show an excess of $^{62}$Ni when data are normalized relative to $^{61}$Ni/$^{58}$Ni. This excess translates into a deficit of $^{61}$Ni when normalizing to $^{62}$Ni/$^{58}$Ni and is interpreted as a nucleosynthetic anomaly.

Discussion: The CAIs display correlated anomalies of $^{60}$Ni and $^{62}$Ni coupled with effects on $^{96}$Zr. Iron-60 is produced in significant amounts together with $^{62}$Ni and $^{96}$Zr in a stellar environment, but not $^{60}$Ni. Therefore, the $^{60}$Ni excess is more likely to result from decay of $^{60}$Fe. The effects show the signature of neutron-burst nucleosynthesis in a massive star. Such a neutron burst is plausibly responsible for the abundance of many short-lived radioactivities present in the early solar system.

A two-point internal isochron for an Allende CAI showing no nucleosynthetic anomaly yields a slope of $3.4 \times 10^{-7}$ corresponding to a lower limit for the initial $^{60}$Fe/$^{56}$Fe of the solar system. However, based on the mineralogy of this CAI, the Fe-Ni system has probably re-equilibrated. An independent estimate can be derived from two bulk CAIs with no nucleosynthetic anomaly and characterized by the same $^{26}$Al/$^{27}$Al initial ratio. An initial $^{60}$Fe/$^{56}$Fe higher than $1.8 \times 10^{-6}$ is inferred if both CAIs formed from the same isotopically homogeneous reservoir. This is higher than previous estimates and consistent with the results of the nucleosynthetic modelling. It would also indicate that $^{60}$Fe played a major role as a heat source to melt planetesimals. However, more data are needed to demonstrate that such an inference from two CAIs is correct.