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HIGHLY ^{15}N-ENRICHED CHONDRITIC CLASTS IN THE ISHEYEVO METEORITE

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The metal-rich carbonaceous chondrites (CB and CH) have the highest whole-rock ^{15}N enrichment[1,2,3] (δ^{15}N up to +1500‰), similar to δ^{15}N values reported in micron-sized regions (hotspots) of Interplanetary Dust Particles (IDPs) of possibly cometary origin and fine-grained matrices of unmetamorphosed chondrites[4,5,6,7]. These ^{15}N-rich hotspots are commonly attributed to low-temperature ion-molecule reactions in the protosolar molecular cloud or in the outer part of the protoplanetary disk[4,5,6,7]. The nature of the whole-rock ^{15}N enrichment of the metal-rich chondrites is not understood. We report a discovery of a unique type of primitive chondritic clasts in the CH/CB-like meteorite Isheyevo[1], which provides important constraints on the origin of ^{15}N anomaly in metal-rich chondrites and nitrogen-isotope fractionation in the Solar System. These clasts contain tiny chondrules and refractory inclusions (5-15 µm in size), and abundant ferromagnesian chondrule fragments (1-50 µm in size) embedded in the partly hydrated, fine-grained matrix material composed of olivines, pyroxenes, poorly-organized aromatic organics, phyllosilicates and other hydrous phases. The mineralogy and oxygen isotope compositions of chondrules and refractory inclusions in the clasts are similar to those in the Isheyevo host, suggesting formation at similar heliocentric distances. In contrast to the previously known extraterrestrial samples, the fine-grained material in the clasts is highly and rather uniformly enriched in ^{15}N, with bulk δ^{15}N values ranging between +1000 and +1300‰; the δ^{15}N values in rare hotspots range from +1400 to +4000‰. Since fine-grained matrices in the lithic clasts are the only component containing thermally unprocessed (during CAI- and chondrule formation or during impact melting) materials that accreted into the metal-rich chondrite parent body(ies), the ^{15}N-enriched clasts as present in Isheyevo probably represent the major primordial carrier of ^{15}N anomaly in these meteorites. The rather uniform and very high bulk ^{15}N enrichment of the Isheyevo chondritic clasts, in contrast to rare hotspots of possibly molecular cloud origin in cometary IDPs, indicates that the nitrogen-isotope fractionation recorded by these clasts, containing abundant solar system materials, could have resulted from processes in the protoplanetary disk (e.g., ultraviolet photodissociation of $^{15}N_2$ followed by trapping ^{15}N atoms into NH-bearing ices) rather than solely by inheritance from the protosolar molecular cloud. If this is the case, the unique ^{15}N-rich signature of the clasts could have resulted from nitrogen-isotope fractionation in cold and optically thin parts of the protoplanetary disk.

The metal-rich carbonaceous chondrites, CH (ALH 85085-like), CB (Bencubbin-like), and Isheyevo show many anomalous characteristics not observed in other chondrite groups, including the largest whole-rock enrichment in ^{15}N, lack of interchondrule fine-grained matrix material (chondritic lithic clasts are present instead), and significant variations in textures and sizes of chondrules[1,8,9]. The CH chondrites contain porphyritic and non-porphyritic ferrous and magnesian chondrules and very refractory calcium-aluminum-rich inclusions (CAIs)[8] of small sizes (20−100 μm). The CB chondrites contain larger chondrules (0.1−7 mm), which have almost exclusively non-porphyritic (cryptocrystalline and skeletal) textures and magnesium-rich compositions[9]. The recently discovered metal-rich chondrite Isheyevo is composed of components that are chemically and mineralogically similar to those in both groups; it is classified as a CH/CB-like meteorite[1,10,11,12].

Based on the young absolute ages of the CB chondrules (4562.7±0.5 Myr), single-stage formation, and the lack of interchondrule, fine-grained matrix material, it was concluded that CB chondrite components formed from a vapor−melt plume produced by a giant impact between planetary embryos after the dusty, protoplanetary disk had largely dissipated[13,14]. The CH chondrites represent a mixture of the impact-produced material (magnesian non-porphyritic chondrules and chemically-zoned Fe,Ni-metal condensates) and nebular components, such as porphyritic chondrules and CAIs formed by thermal processing of dust in the protoplanetary disk[11,15]. The nature of the whole-rock ^{15}N enrichment of metal-rich chondrites is not understood. In order to search for the ^{15}N-rich carrier(s) in metal-rich chondrites, we studied ~ 30 cm^2 of polished thick sections of the Isheyevo meteorite using optical and scanning electron microscopy, electron probe microanalysis, Raman spectroscopy, and ion microprobe (for details see Analytical Techniques section in on-line material). An electron-transparent thin section was extracted from one of the lithic clasts using an FEI Nova600 NanoLab dual-beam FIB (focused ion beam instrument) and studied by scanning transmission electron microscopy (200kV FEI Tecnai TF20 G2) at Lawrence Livermore National Laboratory. We focused our study on the chondritic lithic clasts – the only component in the metal-rich chondrites containing fine-grained matrix[1,12].

About 60 chondritic lithic clasts were identified in the Isheyevo samples studied. Most of the clasts are completely hydrated (contain no anhydrous silicates) and consist of framboidal and platy magnetite, lath-shaped sulfides, and carbonates (dolomite and magnesite) embedded in a

phyllosilicate-rich matrix (Fig. SOM1). Six clasts have distinctly different textures and mineralogy. These are breccias containing numerous fragments, up to 50 μm in size, of porphyritic and non-porphyritic chondrules composed of ferromagnesian olivine and pyroxene, microchondrules and microCAIs (5–15 μm in apparent diameter), and metal-sulfide grains embedded in a fine-grained matrix composed of phyllosilicates and other hydrous phases, poorly-organized aromatic organics, and sub-μm-sized olivines and pyroxenes (Figs. 1, SOM2). Several ferromagnesian cryptocrystalline chondrules contain inclusions of euhedral Fe,Ni-metal. Similar chondrules with inclusions of euhedral Fe,Ni-metal have been described previously only in CH chondrites[16] and the Isheyevo host[1]. The brecciated nature of the clasts can be recognized in backscattered electron images. Some of the clasts with anhydrous silicates contain rare fragments of completely hydrated materials or individual grains of magnetite and carbonates. Our preliminary FIB+TEM studies of fine-grained matrix of the clasts indicate that it also experienced extensive aqueous alteration, but to a lesser degree than the heavily-hydrated clasts or their fragments. This matrix consists of regions containing phyllosilicates (smectites with ~12Å basal spacings), domains of cronstedtite (~7Å basal spacings) intergrown with a poorly-ordered material, possibly tochilinite (with domains of 5Å spacings plus minor Ni and S), and regions of an amorphous Fe-rich phase compositionally consistent with ferrihydrite. Embedded within are anhydrous silicates, magnesian olivines, low-Ca pyroxenes and occasional high-Ca pyroxenes, ranging in size from tens of nanometers to several microns and exhibiting hydrous alteration on their peripheries. Pseudomorphic replacement of minerals, particularly silicates, is evident in many places (Fig. SOM3).

Oxygen-isotope compositions of the ferromagnesian chondrules and chondrule fragments, and two refractory inclusions [one CAI and one amoeboid olivine aggregate (AOA)] from five chondritic lithic clasts were measured with the University of Hawai‘i Cameca ims-1280 ion microprobe. The obtained data are listed in Table SOM1 and, together with data for chondrules[11] and CAIs[11] from the Isheyevo host, are plotted on a three-isotope oxygen diagram, $\delta^{17}O$ *vs.* $\delta^{18}O$ in Figure 2. Oxygen-isotope compositions of the chondrules and chondrule fragments in the clasts are similar to those of the Isheyevo chondrules[11] and plot along the slope-1 line, slightly below and above the terrestrial fractionation line. The CAI and AOA in the clasts are ^{16}O-enriched relative to the chondrules; they are compositionally similar to typical CAIs from Isheyevo[10].

Scanning isotope images of H^-, $^{12}C^-$, $^{13}C^-$, $^{12}C^{14}N^-$, $^{12}C^{15}N^-$, $^{18}O^-$, and $^{28}Si^-$ were acquired using the University of Hawai'i Cameca ims-1280 for ten 50×50 μm^2 regions in the Isheyevo lithic clasts: four in two clasts with anhydrous silicates and six in three heavily-hydrated clasts. Two regions in the CI carbonaceous chondrite Orgueil were also measured for comparison. The $^{12}C^{15}N^-/^{12}C^{14}N^-$ ratio inferred from the obtained images was used to calculate $\delta^{15}N$ value relative to a $^{15}N/^{14}N$ ratio in terrestrial atmosphere. The distributions of $\delta^{15}N$ in four regions of the Isheyevo clasts are shown in Figure 3. The estimated bulk $\delta^{15}N$ and $\delta^{13}C$ values in all measured regions of the Isheyevo lithic clasts and Orgueil are shown in Figure 4. Both lithic clasts with anhydrous silicates show relatively uniform enrichment in ^{15}N; bulk $\delta^{15}N$ values in these regions range from +1000‰ to +1300‰. Two of the regions in these clasts contain mineralogically distinct units (lithologies), indicative of their brecciated nature, which can be recognized in backscattered electron images (Figs. 3d, f). In these cases, the absolute value of $\delta^{15}N$ differs between the lithologies (Figs. 3c, e). Clasts with anhydrous silicates also contain several hotspots with $\delta^{15}N$ values ranging from ~ +1400‰ to ~ +4000‰. The completely hydrated lithic clasts have much less ^{15}N-enriched bulk compositions ($\delta^{15}N$ ~ +300‰) (Figs. 3a,b). They also contain hotspots, which, however, are less ^{15}N-rich than those in clasts with anhydrous silicates. The carbon-isotope composition of both types of clasts are indistinguishable from the terrestrial carbon standard (Fig. 4).

Raman spectra acquired for fine-grained matrices of the completely hydrated clasts and clasts with anhydrous silicates exhibit poorly-defined D- (~1350 cm^{-1}) and G-bands (~1580 cm^{-1}) with a very shallow spectral valley between the two bands (Fig. SOM4). Such spectra are typical for poorly-organized polyaromatic organic matter present in the unmetamorphosed carbonaceous chondrites Orgueil (CI) and Renazzo (CR2), and chondritic IDPs[18], suggesting that both types of clasts avoided thermal metamorphism on their parent body(ies).

Based on the mineralogy, petrography, Raman spectroscopy, and oxygen-isotope compositions of carbonates in the completely hydrated clasts from Isheyevo, we have inferred that they represent fragments of previously unsampled parent bodies[12]. Nitrogen-isotope compositions of these clasts ($\delta^{15}N$ ~ +300‰) differ from those of chondrites that also experienced extensive aqueous alteration (CI, CM, and CR) and support this conclusion.

The Isheyevo clasts with anhydrous silicates are isotopically unique. The fine-grained matrices of these clasts have relatively uniform enrichment in ^{15}N to a level previously observed

only as hotspots in cometary IDPs and primitive chondrite matrices (up to ~ +1300‰). The $\delta^{15}N$ values of hotspots in the Isheyevo clasts are even more extreme (up to ~ +4000‰). The mineralogy, petrography, and oxygen isotope compositions of chondrules and CAIs from the clasts with anhydrous silicates are similar to some of the components in the Isheyevo host and CH chondrites, suggesting a genetic relationship between these materials. However, the interchondrule, fine-grained matrices are not observed in metal-rich chondrites. We conclude that the Isheyevo clasts with anhydrous silicates represent a new type of primitive (unmetamorphosed) material of cometary or asteroidal origin, which may have accreted in close proximity to the Isheyevo meteorite parent body.

The existence of highly ^{15}N-enriched primitive materials sampled by the Isheyevo clasts may provide a clue for the whole-rock ^{15}N enrichment of metal-rich chondrites. Since fine-grained matrices in chondritic lithic clasts are apparently the only thermally unprocessed materials that accreted into the metal-rich chondrite parent body(ies), the ^{15}N-enriched clasts probably represent the major primordial carrier of ^{15}N anomaly in these meteorites. The rare occurrences of such a primordial carrier of ^{15}N anomaly in metal-rich chondrites could be due to the highly energetic event invoked for the origin of chondrules and metal grains (planetary scale collision) in CH and CB chondrites[14], and/or postaccretionary shock metamorphism[18,19]. Both processes could have destroyed the original carrier and redistributed the ^{15}N-rich signature[18,19].

The nitrogen isotopic composition of the Sun is not yet known. The isotopically light nitrogen composition of the Jupiter's atmosphere ($\delta^{15}N$ ~ −300‰) – the second largest nitrogen reservoir in the Solar System[20] and the similar nitrogen-isotope composition of a high-temperature nebular condensate (TiN−TiC solid solution) in a CAI from the Isheyevo meteorite[21] indicate that the average $\delta^{15}N$ value of the solar nebula was probably ~ −300‰. All known chondrite groups (carbonaceous, ordinary, and enstatite) are ^{15}N-enriched[22] relative to this value. The Isheyevo chondritic clasts have the highest bulk ^{15}N enrichment ever measured and thus have important implications for understanding the origin of nitrogen-isotope fractionation recorded by the primitive extraterrestrial materials.

Two different astrophysical settings, in the protoplanetary disk and in the protosolar molecular cloud, were proposed to explain nitrogen-isotope fractionation. According to the disk models[23,24], ultraviolet radiation of the young protoSun resulted in preferential photodissociation of $^{15}N_2$ molecules; the released ^{15}N atoms were chemically trapped into NH-bearing ices at low

temperatures. According to the molecular cloud model, large ^{15}N fractionation ($\delta^{15}N$ up to 10,000‰) can occur in ammonia ices in cold (<10 K), CO-depleted, dense ($nH_2 = 5\times10^6$ cm^{-3}) cloud cores, if most of the nitrogen is atomic[25]. In both models, the ^{15}N-rich signature of ammonia ices was later transferred into more complex molecules and preserved in solids. Further studies of ^{15}N-rich materials in the clasts using transmission electron microscopy and NanoSIMS will reveal the exact carrier(s) of ^{15}N-rich signature.

Several lines of evidence suggest that the bulk ^{15}N enrichment of this special type of Isheyevo clasts is fundamentally different from the rare ^{15}N-rich "hotspots" found in IDPs and primitive chondrite matrices and commonly assigned a molecular cloud origin. First, these large ^{15}N enrichments are apparently unique to metal-rich chondrites, suggesting a relatively "local" origin. Second, the clasts are rather uniformly enriched in ^{15}N (except rare hotspots) to a very high degree, up to 1800‰ relative to the inferred solar value[20,21]. This implies that the ^{15}N enrichment is due to a process that affected a large fraction of nitrogen in the clasts. The uniform distribution of ^{15}N enrichment in fine-grained material may either reflect uniform distribution of the primordial carrier throughout the clasts (molecular cloud or solar nebula in origin) or subsequent re-distribution of ^{15}N anomaly, e.g., during aqueous alteration experienced by the clasts. Third, the clasts contain a large fraction of solar-system material (crystalline olivine and pyroxene, chondrule fragments and refractory inclusions) and thus cannot solely represent the molecular cloud material. Taken together, these lines of evidence may suggest it is more like that the ^{15}N enrichment originated in the protoplanetary disk than was solely inherited from the Sun's molecular cloud.

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Figure 1. Backscattered electron images of a chondrite lithic clast I4_LC8 with anhydrous silicates from the metal-rich carbonaceous chondrite Isheyevo. Regions outlined in "a" are shown in detail in "b" and "c". Regions outlined in "b" and "c" correspond to areas sputtered during oxygen-isotope measurements. The clast contains consists of chondrule fragments, microchondrules, and CAIs embedded in a fine-grained, matrix material. chd = chondrule; fr = chondrule fragments; mel = melilite; met = Fe,Ni-metal; ol = olivine; pv = perovskite; sp = spinel; w = terrestrial weathering products.

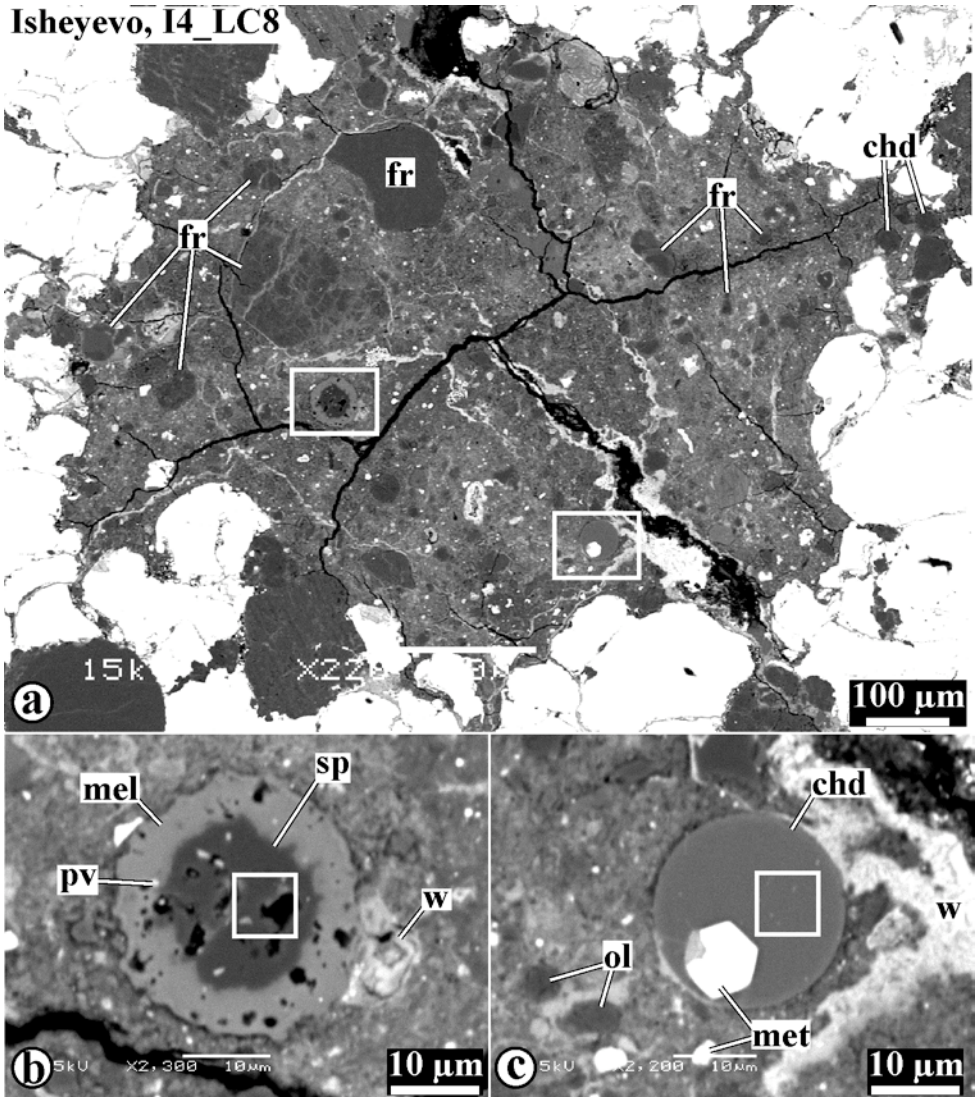


Figure 2. Oxygen-isotope compositions of chondrules and refractory inclusions [Ca,Al-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs)] from the lithic clasts with anhydrous silicates and the host meteorite Isheyevo. $\delta^{17,18}O = ({}^{17,18}O/{}^{16}O_{sample}/{}^{17,18}O/{}^{16}O_{SMOW} - 1) \times 1000$, where SMOW is Standard Mean Ocean Water. 2σ errors for $\delta^{17}O$ and $\delta^{18}O$ are < 1 and 1.5‰, respectively (see Table SOM1). Data for CAIs and chondrules from the Isheyevo host are from [10] and [11], respectively.

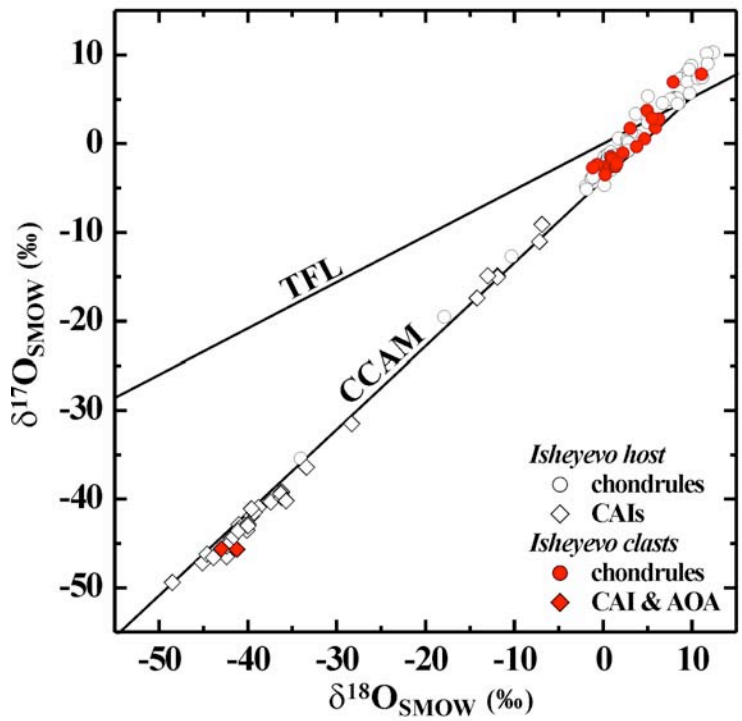


Figure 3. Distribution of $\delta^{15}N$ in the heavily-hydrated chondrite clasts I4_LC12 (a) and I4_LC13 (b) and clasts with abundant anhydrous silicates I7_LC23 (c) and I7_LC22 (e) from the Isheyevo meteorite. Backscattered electron images of the mapped regions in I7_LC23 and I7_LC22 are shown in "d" and "f", respectively. The clasts with anhydrous silicates are enriched in ^{15}N compared to the heavily-hydrated clasts. The ^{15}N enrichment is rather uniform throughout the mapped regions; it correlates, however, with the presence of different lithologies in the clasts. Boundaries between the lithologies are outlined in "d" and "f". The hotspots (some are indicated by arrows in "a", "b", "c", and "e") are observed in both types of clasts; the $\delta^{15}N$ values of hotspots are higher in clasts with anhydrous silicates. Note that black regions in "c" and "e" are masked regions with low count rates from which no statistically meaningful ratios can be obtained. mgt = magnetite; ol = olivine; px = low-Ca pyroxene; sf = sulfide.

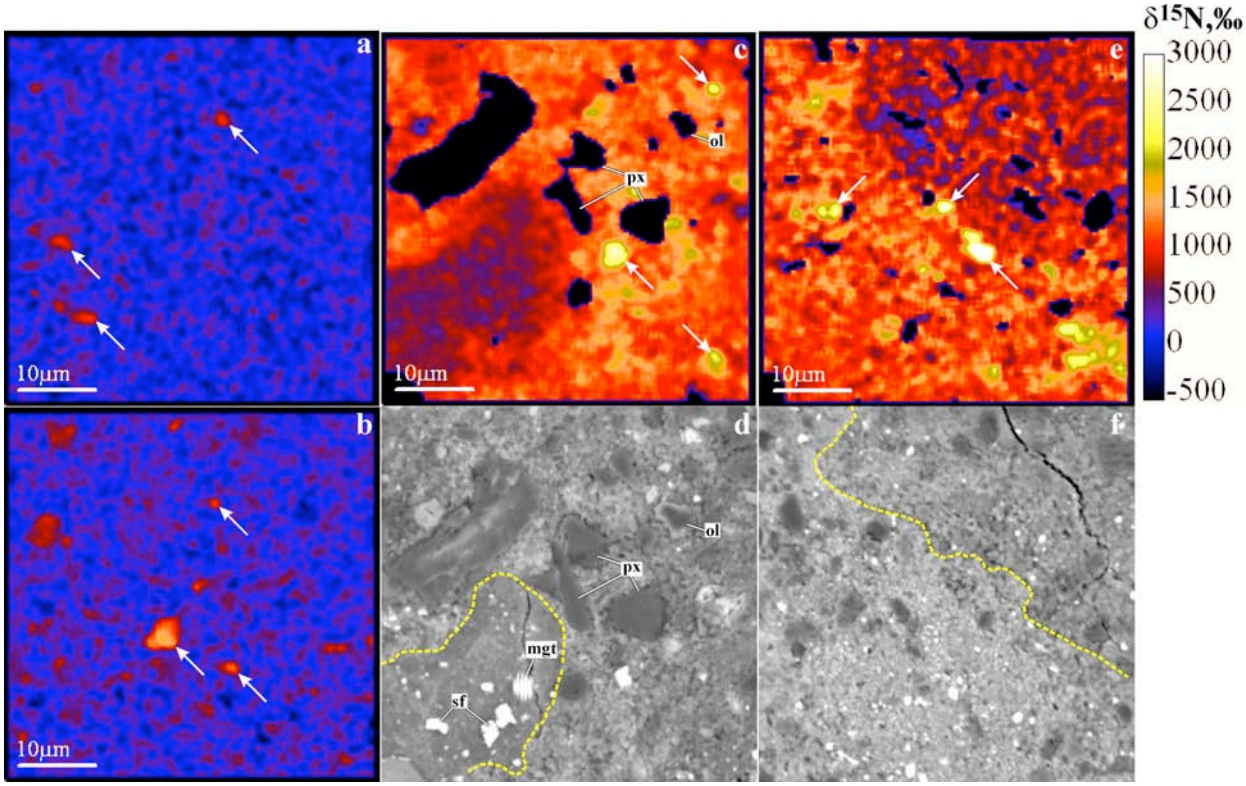
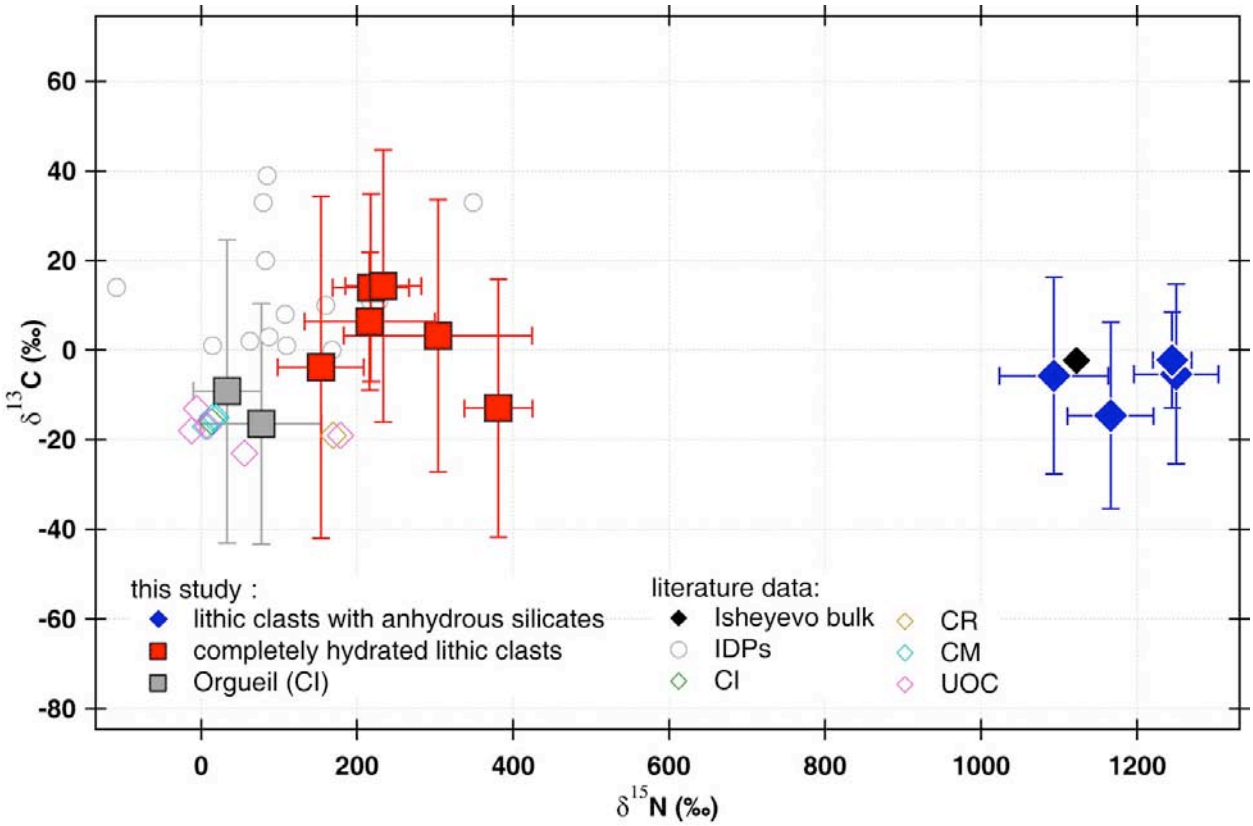


Figure 4. Bulk values of $\delta^{13}C$ *vs.* $\delta^{15}N$ in the Isheyevo clasts with and without anhydrous silicates, Isheyevo host[9], IDPs[7], CI, CR, and CM carbonaceous chondrites, and unequilibrated ordinary chondrites (UOC)[4]. The Isheyevo lithic clasts with anhydrous silicates are compositionally similar to the Isheyevo host; they are highly ^{15}N-enriched compared to the completely hydrated clasts in Isheyevo, IDPs and other chondrite groups. Rough calculations based on our isotope measurements indicate that the clasts with anhydrous silicates have ~3× higher nitrogen content than the completely hydrated clasts; the latter, however, are ~10× more abundant. Taken together, the clasts may provide one-third to one half of the bulk nitrogen in Isheyevo. We infer that although the ^{15}N-rich clasts may be representative of the primordial (thermally unprocessed) material that carried heavy nitrogen in Isheyevo, most of the nitrogen is currently sited in other components of the meteorite[18,19].



Supplementary Online Material

Analytical techniques

Mineralogy and Petrography

Polished thick sections (of ~ 30 cm^2) of the Isheyevo meteorite were mapped in Mg, Ca, and Al Kα x-rays with resolution of 2–5 μm/pixel using the Cameca SX-50 electron microprobe at 15 kV accelerating voltage, 50 nA beam current and ~1–2 μm beam size. These maps were combined using an RGB-color scheme and the ENVI (ENvironment for Visualizing Images) software package. The obtained false color maps were used to identify chondritic lithic clasts. The mineralogy of the clasts was studied in reflected light using an optical microscope and in backscattered electrons using a JEOL 5900LV scanning electron microscope equipped with an energy dispersive x-ray spectrometer (EDS). Chemical compositions of the anhydrous silicates were estimated from EDS.

Oxygen isotope measurements

Oxygen isotopic compositions of 10-15 μm-sized grains were measured using the University of Hawai‘i Cameca ims 1280. A 400 pA Cs^+ primary ion beam was focused to a diameter of ~ 5 μm and rastered over ~ 7×7 μm^2 area for pre-sputtering (100 seconds). After pre-sputtering, the raster size was reduced to 5×5 μm^2 for automated centering of the secondary ion beam followed by data collection. The normal-incidence electron gun was used for charge compensation. Three oxygen isotopes were measured by combination of multicollection mode and peak-jumping. $^{16}O^-$ and $^{17}O^-$ were measured simultaneously using the multicollection Faraday cup (FC) and the monocollection electron multiplier (EM), respectively. Subsequently, $^{18}O^-$ was measured with the monocollection EM by peak-jumping. Mass resolving power (MRP) for $^{17}O^-$ and $^{18}O^-$ was set to ~ 5500. The $^{18}O^-$ secondary ion intensity was typically ~1.5×10^5 counts per second. $^{18}O^-$ was collected for only 3 sec, while $^{16}O^-$ and $^{17}O^-$ were measured for 8 sec. The measurement consisted of 60 cycles. As a further control on the gain of the EM, the pulse-height distribution was checked every 5 measurements. The EM high voltage was adjusted when necessary to maintain a constant pulse-height distribution. Measured count rates were corrected for background (in the case of FC) and deadtime (in the case of EM). The instrumental mass

fractionation (IMF) was corrected for during each measurement session using San Carlos olivine (Fo_{89}) and augite standards.

Carbon and nitrogen isotope scanning imaging

Scanning-ion images of the fine-grained matrix were collected over areas of 50×50 μm^2 in 256×256 pixels. A 30 pA Cs^+ primary beam focused to ~1 μm was used to generate secondary negative ions of H, $^{12}C^-$, $^{13}C^-$, $^{12}C^{14}N^-$, $^{12}C^{15}N^-$, $^{18}O^-$, and $^{28}Si^-$. All ions (except H^-) were measured at MRP of ~ 6000, with a monocollector EM. H^- was measured on a multicollector EM with a MRP of ~ 2000. H^-, $^{12}C^-$, $^{18}O^-$, $^{12}C^{14}N^-$, and $^{28}Si^-$ were measured for 1 second; $^{13}C^-$ and $^{12}C^{15}N^-$ for 30 seconds. The measurements consisted of 600 cycles, the mass calibration being manually checked every 200 cycles. A polished thin section of Orgueil (CI) with bulk nitrogen and carbon isotopic composition reported by [5] was used as a standard. The isotope images thus obtained were processed using L'image software (provided by L. Nittler). Images for all 600 cycles were corrected for possible image shift during measurements and added for each measured species to increase the total signal. Isotope ratio images were obtained by dividing the images of two species (e.g., $^{12}C^{14}N^-$ and $^{12}C^{15}N^-$) pixel by pixel. The isotope ratio images are smoothed over 3×3 pixels to improve the statistical uncertainty. The isotope ratios were verified throughout the individual images of an imaging measurement. This ensures that anomalous compositions seen in the ratio images are not due to a random fluctuation or an artifact of the measurement.

Electron-transparent thin section preparation and transmission electron microscopy

Surface topography in isotope-mapped regions of the clasts was first carefully correlated with $\delta^{15}N$ maps using a high resolution JEOL JSM-7401F field emission scanning electron microscope at Lawrence Livermore National Laboratory. Using an FEI Nova600 NanoLab dual-beam FIB (focused ion beam instrument), a site-specific section was extracted, attached to a TEM grid and thinned to electron transparency. Subsequent transmission electron microscopy analysis was carried out on a 200kV FEI Tecnai TF20 G2 analytical (scanning) transmission electron microscope equipped with a solid state EDAX x-ray energy dispersive detector and a high-resolution Gatan Imaging Filter. Compositions were estimated using energy-dispersive spectroscopy in conjunction with a Cliff-Lorimer thin-film correction procedure.

Table SOM1. Oxygen-isotope compositions of the anhydrous minerals from the Isheyevo clasts.

clast #	mineral/spot #	$\delta^{17}O$	±2σ	$\delta^{18}O$	±2σ	$\Delta^{17}O$	±2σ
I4_LC8	pyroxene #1	−2.6	0.9	0.2	0.8	−2.7	1.0
I4_LC8	olivine #2	−2.4	1.0	−0.7	1.2	−2.0	1.2
I4_LC8	pyroxene #3	3.8	1.0	5.0	0.8	1.2	1.1
I4_LC8	olivine #4	−1.5	1.0	0.9	1.2	−2.0	1.2
I4_LC8	CAI, spinel #5	−45.7	1.0	−41.2	1.2	−24.2	1.2
I7_LC23	pyroxene #1	−2.6	1.3	0.9	1.2	−3.1	1.4
I7_LC23	olivine #2	7.8	1.6	11.1	2.2	2.1	1.9
I7_LC23	pyroxene #3	1.8	1.3	5.9	1.2	−1.3	1.4
I7_LC23	olivine #4	−1.1	1.6	2.2	2.2	−2.2	1.9
I7_LC23	pyroxene #5	2.8	1.2	6.3	1.2	−0.5	1.4
I7_LC23	pyroxene #6	0.6	1.3	4.7	1.3	−1.9	1.4
I7_LC22	AOA, olivine #1	−45.6	1.6	−43.0	2.2	−23.3	2.0
I7_LC22	pyroxene #2	−1.8	1.6	1.0	2.3	−2.3	2.0
I7_LC22	pyroxene #3	−2.6	1.6	1.4	2.3	−3.3	1.9
I8_LC100	pyroxene #1	−0.3	0.6	3.8	0.7	−2.3	0.7
I8_LC100	pyroxene #2	2.9	0.6	5.5	0.6	0.0	0.7
I8_LC100	pyroxene #3	−3.5	0.7	0.2	0.8	−3.6	0.8
I8_LC100	pyroxene #4	−2.5	0.6	1.5	0.7	−3.2	0.7
I8_LC101	pyroxene #1	−2.7	0.7	−1.2	0.7	−2.1	0.8
I8_LC101	pyroxene #2	7.0	0.7	7.9	0.8	2.9	0.8
I8_LC101	pyroxene #3	1.7	0.7	3.0	0.7	0.2	0.8
I8_LC101	pyroxene #4	−2.2	0.6	1.6	0.6	−3.0	0.6

CAI = calcium-aluminum-rich inclusion; AOA = amoeboid olivine aggregate.

Figure SOM1. Backscattered electron images of the heavily-hydrated chondritic clasts I4_LC2 (a, b) and I5g_LC2 (c, d) from Isheyevo. Regions outlines in "a" and "c" are shown in detail in "b" and "d", respectively. The clasts consist of framboidal and platy magnetite, lath-shaped sulfides, carbonates and phosphates embedded in a phyllosilicate-rich matrix. mgt = magnetite; dol = dolomite; sf = sulfide; ph = phosphate; phyl = phyllosilicate.

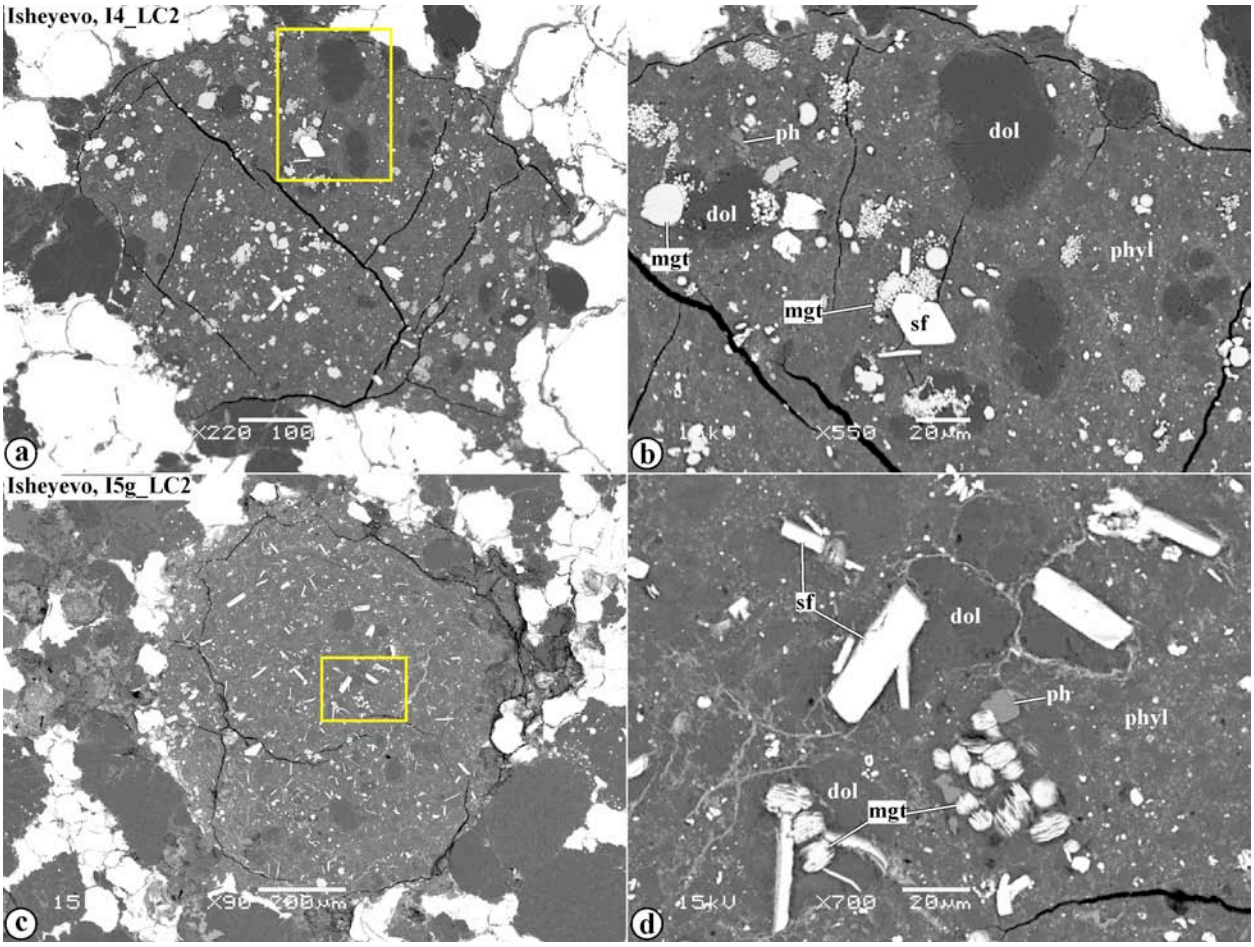


Figure SOM2. Backscattered electron (a) and reflected light (b) images of a clast I8_LC101 with anhydrous silicates from Isheyevo. The presence of metal grains and abundant fragments of anhydrous silicates in a fine-grained matrix of the clast suggests that this clast did not experience complete aqueous alteration. Some metal grains are partly sulfidized. One of the metal grains inside a microchondrule is euhedral. chd = chondrule; fr = fragment; met = Fe,Ni-metal; sf = sulfide.

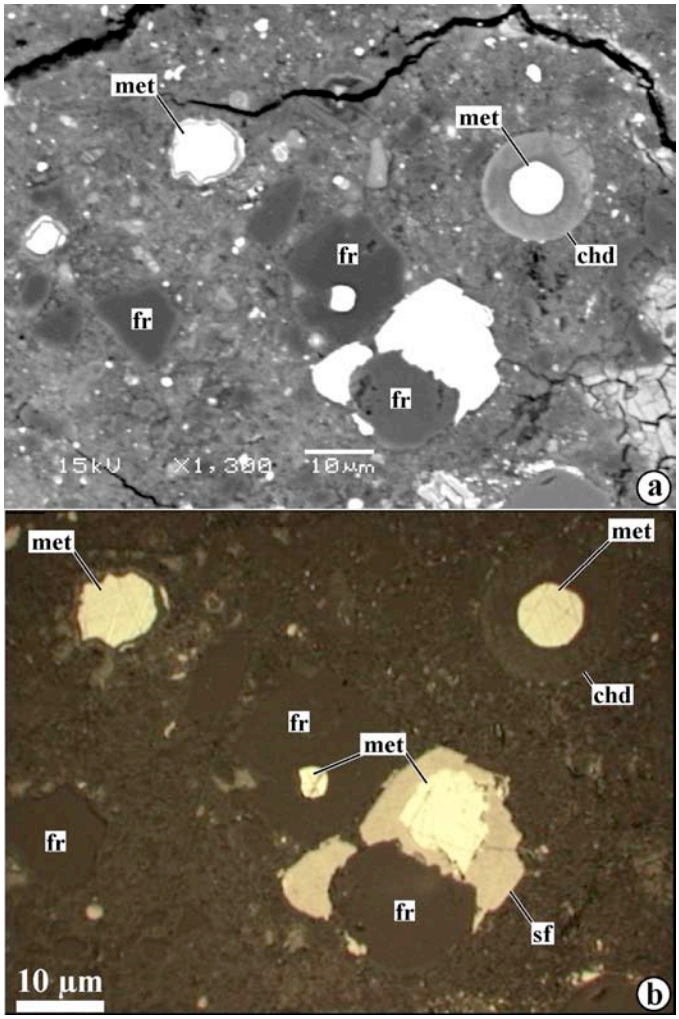


Figure SOM3. Brightfield transmission electron micrographs of the fine-grained matrix of a clast I7_LC23 with anhydrous silicates from Isheyevo (a, b). The region outlined in (a) is shown at higher magnification in (b). A majority of the matrix is hydrous, Fe-rich, amorphous and poorly-ordered and contains secondary magnetite framboids and remnant anhydrous silicates. Anhydrous silicate grains are surrounded by the phyllosilicate products of their aqueous alteration, and pseudomorphic replacement can be observed in many locations (e.g. b). Surviving olivines and pyroxenes tend to be Mg-rich, and those labeled in (b) are $Fo_{\sim 90\text{-}98}$ and $En_{\sim 98}$. mgt=magnetite; px=pyroxene; ol=olivine. [Magnetite identification still needs to be confirmed with diffraction pattern.]

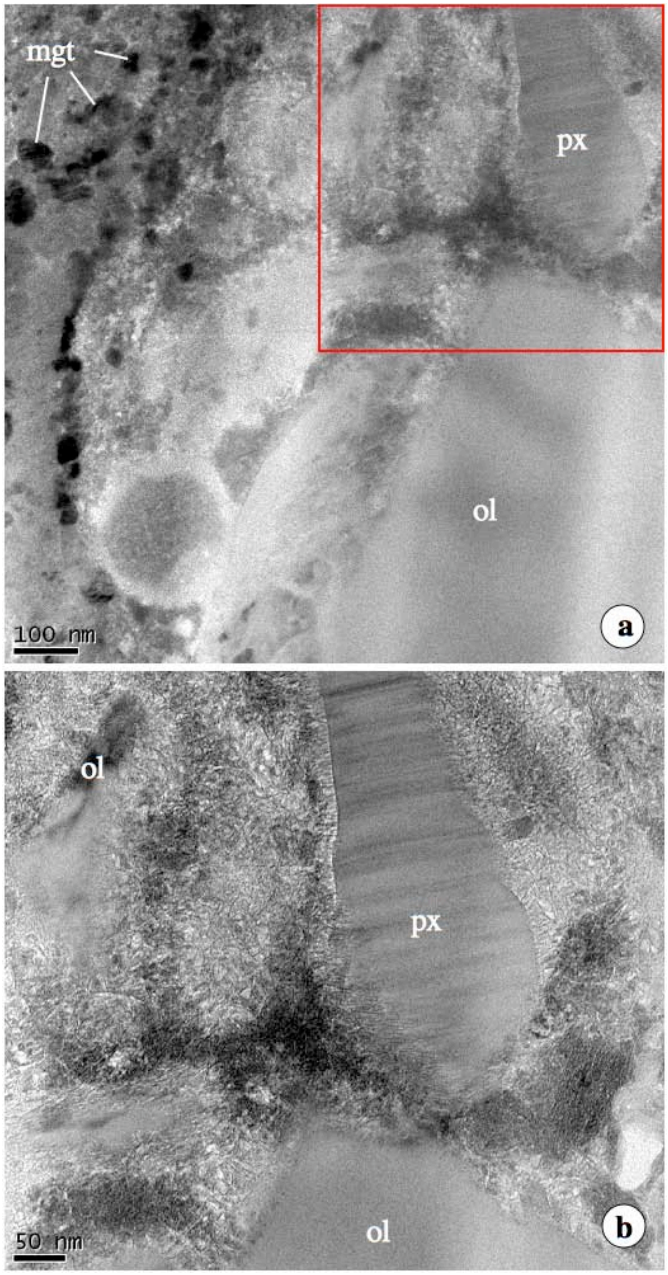
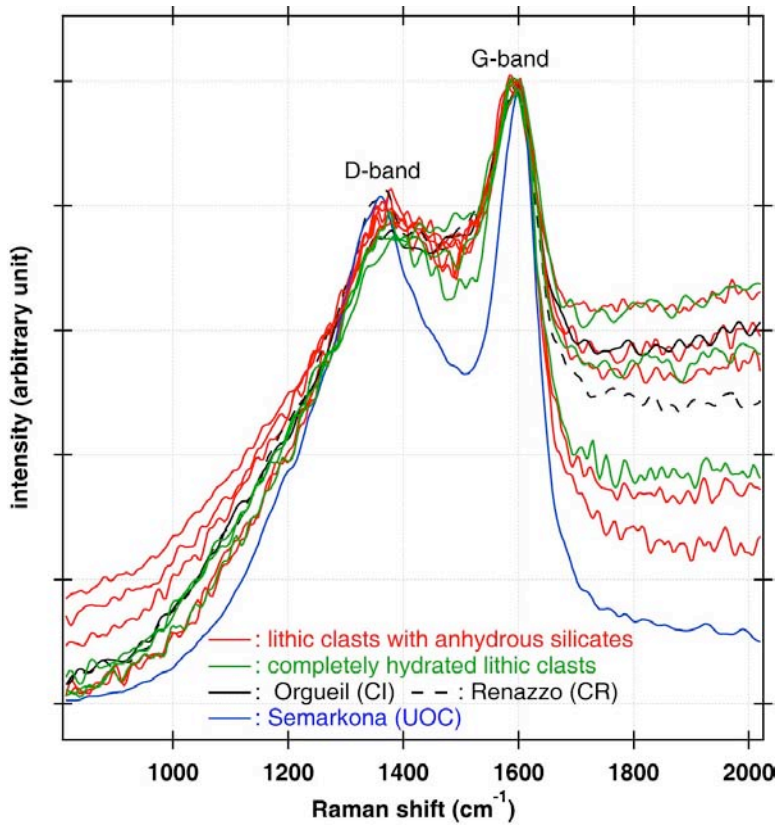



Figure SOM4. Average Raman spectra of the lithic clasts with anhydrous silicates and completely hydrated lithic clasts from Isheyevo compared with the average Raman spectra of Orgueil (CI), Renazzo (CR2), and Semarkona (LL3.0). The Raman spectra of the Isheyevo clasts are similar to those of Orgueil and Renazzo, suggesting that the clasts are not metamorphosed.