Chondritic lithic clasts in the CB/CH-like meteorite Isheyevo: Fragments of previously unsampled parent bodies

Lydie Bonal *, Gary R. Huss, Alexander N. Krot, Kazuhide Nagashima

School of Ocean, Earth Science and Technology, Hawai’i Institute of Geophysics and Planetology, University of Hawai’i at Manoa, Honolulu, HI 96822, USA

Received 8 July 2009; accepted in revised form 6 January 2010; available online 4 February 2010

Abstract

The CB/CH-like chondrite Isheyevo is characterized by the absence of fine-grained interchondrule matrix material; the only present fine-grained material is found as chondritic lithic clasts. In contrast to the pristine high-temperature components of Isheyevo, these clasts experienced extensive aqueous alteration in an asteroidal setting. Hence, the clasts are foreign objects that either accreted together with the high-temperature components or were added later to the final Isheyevo parent body during regolith gardening. In order to constrain the origin and secondary alteration of the clasts in Isheyevo, we studied their mineralogy, petrography, structural order of the polyaromatic carbonaceous matter, and oxygen isotopic compositions of carbonates. Three main groups of clasts were defined based on mineralogy and petrology. Group I clasts consist of phyllosilicates, carbonates, magnetite, and lath-shaped Fe,Ni-sulfides. Group II clasts contain different abundances of anhydrous silicates embedded in a hydrated matrix; sulfides, magnetite, and carbonates are rare. With only a few exceptions, groups I and II clasts did not experience significant thermal metamorphism. Group III clasts are characterized by the absence of magnetite and the presence of Fe,Ni-metal. In addition to aqueous alteration, they experienced thermal metamorphism as reflected by the structure of their polyaromatic carbonaceous matter. While there are some similarities between the Isheyevo clasts, CI chondrites, and the matrices of CM and CR chondrites, on the whole, the characteristics of the clasts do not match those of any of these aqueously altered meteorite classes. Nor do they match those of similar material in various types of chondritic clasts present in other meteorite groups. We conclude that the Isheyevo clasts represent fragments of previously unsampled parent bodies.

© 2010 Elsevier Ltd. All rights reserved.

1. INTRODUCTION

The CH and CB chondrites, often called the metal-rich carbonaceous chondrites, exhibit several anomalous characteristics not observed in other chondrite groups: e.g., (i) large variations in modal abundances and sizes of metal grains and chondrules, (ii) extreme depletion in volatile elements, (iii) large enrichment in siderophile elements (e.g., Weisberg et al., 1990, 2001; Krot et al., 2002, 2003), (iv) the highest whole-rock enrichments in $^{15}$N (e.g., Prombo and Clayton, 1985; Franchi et al., 1986; Grady and Pilinger, 1990, 1993; Weisberg et al., 1995), and (v) nearly complete absence of interchondrule, fine-grained matrix material; the fine-grained material occurs mainly as chondritic lithic clasts (e.g., Grossman et al., 1988; Weisberg et al., 1988; Scott, 1988; Greshake et al., 2002).

The high-temperature components of the metal-rich chondrites – Fe,Ni-metal grains, chondrules, and refractory inclusions [calcium–aluminum-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs)] – are mineralogically pristine and show little evidence for aqueous alteration or thermal metamorphism. All metal-rich chondrites, however, experienced shock metamorphism to varying degrees (e.g., Newsom and Drake, 1979; Weisberg et al., 2001; Rubin et al., 2003; Meibom et al., 2005). The origin of the high-temperature components in CB and CH...
Chondritic lithic clasts in the Isheyevo meteorite

2.1. Mineralogy and petrography

There has been limited work on the mineralogy, petrography, and isotopic compositions of lithic clasts in the CH and CB chondrites. The lithic clasts in the CH chondrites Allan Hills (ALH) 85085 and Acfer 182 are mineralogically similar to the fine-grained matrices of the aqueously altered carbonaceous (CI, CM, CR) chondrites (Grossman et al., 1988; Scott, 1988; Weisberg et al., 1988; Bischoff et al., 1990; Krot et al., 2008a,b). According to the more complex, nebular + asteroidal models, most of the magnesian non-porphyritic (cryptocrystalline and skeletal) chondrules and isolated Fe,Ni-metal grains formed during a single-stage process, possibly in a gas-melt plume produced by a planetary-scale collision (e.g., Campbell et al., 2002; Rubin et al., 2003; Krot et al., 2005). According to the more complex, nebular + asteroidal models, most of the magnesian non-porphyritic (cryptocrystalline and skeletal) chondrules and isolated Fe,Ni-metal grains formed during a single-stage process, possibly in a gas-melt plume produced by a planetary-scale collision, whereas porphyritic chondrules and refractory inclusions formed during multiple transient heating events in the solar nebula (Wasson and Kallemeyn, 1990; Krot et al., 2008a,b).

There has been limited work on the mineralogy, petrography, and isotopic compositions of lithic clasts in the CH and CB chondrites. The lithic clasts in the CH chondrites Allan Hills (ALH) 85085 and Acfer 182 are mineralogically similar to the fine-grained matrices of the aqueously altered carbonaceous (CI, CM, CR) chondrites (Grossman et al., 1988; Scott, 1988; Weisberg et al., 1988; Bischoff et al., 1993; Greshake et al., 2002). They typically consist of frambooidal and platelet magnetite, Fe,Ni-sulfides, and carbonates embedded in a fine-grained, hydrated matrix. Sugiuira and Zashu (2001) reported the presence of isotopically heavy nitrogen (δ15N up to 1500‰) associated with a carbon–silicate aggregate in a lithic clast from the CH chondrite Pecora Escarpment (PCA) 91467. Greshake et al. (2002) described the mineralogy and petrography of lithic clasts in the CB chondrites Queen Alexandra Range (QUE) 94411 and Hammadah al Hamra 237, and the CH chondrites Patuxent Range (PAT) 91546 and ALH 85085. Ivanova et al. (2008) characterized lithic clasts in Isheyevo and emphasized their similarities to those in CI and CB chondrites and to hydrated matrices in CI, and CM carbonaceous chondrites. Because chondrules and refractory inclusions in the metal-rich chondrites show little evidence for hydration (e.g., Prombo and Clayton, 1985; Franchi et al., 1986; Grady and Pillinger, 1990, 1993; Weisberg et al., 1995). The nature of this anomaly is not known. Sugiuira and Zashu (2001) suggested, however, that the clast containing 15N-rich carbon–silicate aggregate in PCA 91467 may have experienced in situ aqueous alteration. The metal-rich chondrites are characterized by the highest whole-rock 15N-enrichment observed to date (e.g., Prombo and Clayton, 1985; Franchi et al., 1986; Grady and Pillinger, 1990, 1993; Weisberg et al., 1995). The nature of this anomaly is not known. Sugiuira and Zashu (2000) suggested that the original 15N-carrier was decomposed during a shock heating event, leading to redistribution of nitrogen and uniform N-isotope ratios. Sugiuira and Zashu (2001) suggested an interstellar origin of carbonaceous material to explain 15N enrichment (δ15N up to ~2500‰) found in carbon–silicate aggregates from the CH chondrite PCA 91467.

Isheyevo is a metal-rich carbonaceous chondrite classified as CB/CH-like meteorite (Ivanova et al., 2008). It contains several lithologies with different relative proportions and sizes of similar chondritic components (Fe,Ni-metal, chondrules, and refractory inclusions). The boundaries between lithologies are either sharp or gradational and the metal-rich lithologies are dominant (Ivanova et al., 2008). The metal-rich (>70 vol% of metal) and metal-poor (<20 vol% of metal) lithologies show mineralogical, chemical and isotopic similarities to CB and CH chondrites, respectively (Krot et al., 2007a,b, 2008a,b; Ivanova et al., 2008). Isheyevo is characterized by the highest bulk δ15N value among metal-rich chondrites (δ15N up to 1500‰; Ivanova et al., 2008).

In order to understand the origin of lithic clasts in metal-rich chondrites and search for the carrier(s) of 15N-anomaly in these meteorites, we initiated a detailed study of lithic clasts in Isheyevo using optical and scanning electron microscopy (SEM), Raman spectroscopy, electron microprobe analyzer (EPMA), and secondary ion mass spectrometry (SIMS). Our preliminary studies of the Isheyevo lithic clasts showed large diversity in their mineralogy and aqueous alteration and thermal history (Bonal et al., 2007b, 2008a). Here we report on the mineralogy and petrography of the lithic clasts, the structural order of the included polyaromatic carbonaceous matter, and oxygen isotopic compositions of their carbonates.

2. SAMPLES AND ANALYTICAL PROCEDURES

Six polished thick sections of Isheyevo (Is, I1, I4, I5g, I7, and I8) were mapped with a resolution of 1–10 µm/pixel in Ca, Al, Mg, Na, Si, and Cl Kα X-rays using the UH Cameca SX-50 electron microprobe operated at 15 keV accelerating voltage, with a 50–100 nA beam current and ~1–2 µm beam size. The elemental maps in Mg, Ca, and Al Kα were combined using a RGB-color scheme and ENVI software. Using these maps, all lithic clasts >10 µm in size were identified.

2.1. Mineralogy and petrography

The mineralogy of the clasts was studied in reflected light and in backscattered electron images using the UH JEOL 5900LV scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). Because the samples are thick, none of the clasts was studied in transmitted light.

Chemical compositions of carbonates in 19 lithic clasts were measured with a Cameca SX-50 electron microprobe using focused beam (about 2 µm), 15 kV accelerating voltage, and a beam current of 10 nA. The standards included dolomite for Mg, calcite for Ca, rhodochrosite for Mn, magnesite for Mg and Fe, and chromite for Cr. The detection limits were (in wt%) SiO2: 0.04; CaO: 0.05; MgO: 0.07; MnO, FeO: 0.11, and Cr2O3: 0.13.
The elemental compositions of the fine-grained matrices in 23 clasts were also measured with the Cameca SX-50 electron microprobe using the same conditions as for the carbonates. Standards included anorthite for Al, diopside for Ca and Si, San Carlos olivine for Mg, fayalite for Fe, verma garnet for Mn, albite for Na, orthoclase for K, chromite for Cr, sphene glass for Ti, and troilite for S. The detection limits were (in wt%): SiO\(_2\), Al\(_2\)O\(_3\), MgO: 0.03; TiO\(_2\), CaO, K\(_2\)O: 0.04; Na\(_2\)O, Cr\(_2\)O\(_3\): 0.06; MnO: 0.07; FeO: 0.08, SO\(_2\): 0.09.

Chemical compositions of large anhydrous silicates were measured in four different lithic clasts using the UH field emission JEOL JXA-8500F electron microprobe at 15 keV acceleration voltage, 20 nA beam current and fully focused beam (\(\sim\)100 nm in size) using wavelength dispersive X-ray spectroscopy. The same natural standards as for phyllosilicates were used.

For all electron probe analyses, matrix effects were corrected using ZAF matrix correction procedures.

2.2. Structural characterization of the polyaromatic carbonaceous matter

The structural order of the polyaromatic carbonaceous matter in the clasts was characterized by Raman spectroscopy. Raman spectra were acquired with the confocal Raman microscope (alpha-300, WITec) located at UH, using the 532 nm excitation wavelength of a frequency-doubled solid-state Nd:YAG laser. The laser beam was focused on the samples by a 100\(\times\) objective, leading to a \(\sim\)2 \(\mu\)m diameter spot.

The reproducibility of Raman measurements on poorly organized polyaromatic carbonaceous matter is affected by atmospheric conditions, irradiation time, and power on the sample, due to photo-oxidation effects during irradiation (Quirico et al., 2005). To minimize these affects, the Raman spectra of Isheyevo, Orgueil (CI1), Renazzo (CR2), and Semarkona (LL3.0) were acquired in the same experimental conditions (Orgueil, Renazzo, and Semarkona were used as reference samples). Moreover, carbonaceous material, which is opaque, is characterized by a high extinction coefficient of visible light. Therefore, the visible light from the laser beam excites Raman scattering in the upper most several tens to hundred nanometers of the carbonaceous material. This may result in laser-induced heating of this material (e.g., Lespade et al., 1984), and because the carbonaceous matter is very sensitive to the laser-induced heating, it can potentially be locally altered. To minimize this effect, the power of the laser (400 \(\mu\)W on the sample surface) was tuned such that spectra from a single spot were reproducible over time and no crater corresponding to the laser impact at the sample surface was visible. The structural order of the surface layer of carbonaceous matter can also be potentially modified during sample preparation, especially during polishing. However, a systematic study of poorly organized organic matter in terrestrial and extraterrestrial samples shows no significant difference between data obtained on raw samples and polished sections (Fig. 1). We are therefore confident that our data on Isheyevo clasts from different polished sections can be compared to each other and to the chondrites used as reference samples.

Each spectrum was acquired in a spectral window of 400–3200 cm\(^{-1}\) (shift relative to the laser wavelength). The calibration of the spectrometer was checked daily on a silicon wafer before measurements on the clasts. Each acquisition consisted of three integrations of 10 s each. The three integrations were averaged to make the final spectrum. This technique permits monitoring of the sample for beam damage. For each clast, between 40 and 100 spectra, depending on the size of the clast, were acquired.

![Fig. 1. Raman spectra obtained on a polished section and raw sample of terrestrial anthracite. No spectral differences are visible between the two kinds of preparation: in that range of maturity (and lower), no artifact are induced by the polishing process. Terrestrial coals are used as comparison standards of the polyaromatic carbonaceous matter present in chondrites. Data from E. Quirico and S. Duber.](image-url)
2.3. Oxygen isotopic composition of carbonates

Oxygen isotopic compositions of 10 carbonate grains (dolomite and magnesite) larger than 20 μm in diameter in seven lithic clasts from three different polished thick sections were analyzed in situ with the UH Cameca ims-1280 ion microprobe. Ion microprobe pits were documented by SEM.

A 1.8–1.2 nA focused Cs⁺ primary ion beam was first rastered over a 25 × 25 μm² area for 250 s. The raster was then reduced to 10 × 10 μm² to collect the data. Secondary ions of ¹⁶O⁻, ¹⁷O⁻ and ¹⁸O⁻ were measured simultaneously in multicollection mode with the magnetic field controlled by a nuclear magnetic resonance (NMR) probe. Signals of ¹⁶O⁻ and ¹⁸O⁻ were measured by multicollector Faraday cups (FCs) with low mass resolving power (MRP ~2000), while ¹⁷O⁻ was measured using the axial monocollector electron multiplier (EM) in pulse counting mode with MRP ~5600, which is usually sufficient to separate the interfering ¹⁶OH⁻ signal. Typical count rates of ¹⁶O⁻ and ¹⁷O⁻ ion beams were ~5.8 × 10⁵ and ~2.5 × 10⁵ cps, respectively. The relatively high count rate of the ¹⁷O⁻ signal may produce a drop in gain due to aging of a first dynode of the EM. To minimize this effect, the ¹⁷O⁻ signal was measured for only 4 s in each cycle, after which the beam was deflected into a monocollector FC for 10 s (procedure originally proposed by Kita et al., 2007). Signals for ¹⁶O⁻ and ¹⁷O⁻ collected during the 4-s interval were used to determine the ¹⁶O/¹⁷O ratio and the ¹⁶O⁻ and ¹⁸O⁻ signals collected during the 10-s interval were used to determine the ¹⁸O/¹⁶O ratio. Each measurement consisted of 40 cycles. As a further control on the gain of the EM, the pulse-height distribution was checked every five measurements and the EM high voltage was adjusted when necessary to maintain a constant pulse-height distribution. Measured count rates were corrected for background (in case of FC) and dead-time (in case of EM). The normal-incidence electron gun was used for charge compensation.

Because thick sections of the samples were measured, the vacuum in the sample chamber of the ion probe was higher than we normally have (~1.5 × 10⁻⁸ vs. ~1.0 × 10⁻⁹ torr), resulting in a ¹⁶OH⁻ peak much higher than we normally see. The contribution of the tail of ¹⁶OH⁻ to the ¹⁷O⁻ peak was systematically monitored after each measurement and a correction was made when necessary. The required correction varied between 0.8 and 2.5%. A nitrogen trap was used in a second set of analyses, allowing a better vacuum (3.8 × 10⁻⁹ vs. 1.5 × 10⁻⁸ torr). Unfortunately, this did not significantly decrease the contribution of ¹⁶OH⁻ to the ¹⁷O⁻ peak.

All data were corrected for instrumental mass fractionation (IMF) using natural carbonate minerals: calcite UWC3 and dolomite 6250 kindly provided by Noriko Kita and John Valley (University of Wisconsin), Calcite and dolomite data were corrected for IMF using the known δ¹⁸O value of standards. Magnesite data were corrected by using the relative difference of IMF between dolomite and magnesite reported by Leshin et al. (1998).

To assess the reliability of our analytical protocol, we measured the oxygen isotopic compositions of carbonates in the CM2 chondrite Murchison (section UH68). The contribution of the tail of ¹⁶OH⁻ to the ¹⁷O⁻ peak was also systematically monitored after each measurement. This contribution was significantly lower than for the Isheyevo carbonates. The required correction was typically 0.8% and always less than 0.9%. The reported uncertainties include both the internal measurement precision on an individual analysis and the external reproducibility for standard measurements during a given analytical session. These data are compared to the compositions of Murchison calcite grains previously obtained by gas source mass spectrometry (Clayton and Mayeda, 1984; Benedix et al., 2003) in Fig. 2. Our measurements are reproducible and fall at the ¹⁸O-rich end of the array of previous measurements. We do not observe the range of δ¹⁸O values reported by Benedix et al. (2003). One possibility for this difference is incomplete CO₂ yields in earlier studies. In these studies, CO₂ was released from carbonates by reaction with phosphoric acid in the extraction line (Clayton and Mayeda, 1984; Benedix et al., 2003). Fig. 3 shows a strong correlation between the CO₂ yield and δ¹⁸O from these two studies. The most ¹⁸O-rich sample is the one with the highest yield and the one that falls within the cluster of our measurements. The data in Fig. 3 imply that the oxygen isotopic composition becomes more ¹⁸O-rich with increasing extraction efficiency and that when the CO₂ from calcite is completely extracted, the resulting composition matches that measured in individual calcite grains. The agreement between our data and previous measurements with the highest yields gives us confidence that our data are reliable. In the following discussion, the only data we consider from Benedix et al. (2003) are the ones with the highest CO₂ yields.

Fig. 2. Comparison of the oxygen isotopic composition of calcite grains from the Murchison CM2 chondrite obtained by SIMS in the present study (black diamonds, error bars = 2σ) and gas source mass spectrometry. Open grey diamonds are data from Benedix et al. (2003); plain grey diamond is a datum from Clayton and Mayeda (1984). The terrestrial fractionation line is shown for reference. The data acquired in the present study are reproducible. The range of δ¹⁸O values reported by Benedix et al. (2003) is not observed. This difference is discussed in the text.
3. RESULTS

For the sake of discussion, we classified the clasts into three arbitrary groups according to their petrography and mineralogy. They were also independently classified into two groups according to their Raman spectra. This is not an attempt to define a new classification scheme, but only to provide a way for the reader to understand the characteristics of the Isheyevo clasts.

3.1. Mineralogy and petrography

Isheyevo is a metal-rich carbonaceous chondrite that contains several lithologies with different abundances of Fe,Ni-metal (7–90 vol%). The metal-rich lithologies with 50–60 vol% of Fe,Ni-metal are dominant. The metal-rich and metal-poor lithologies are most similar to the CB and CH carbonaceous chondrites, respectively (Ivanova et al., 2008; Krot et al., 2007a,b, 2008a,b). Among the sections we studied, different lithologies can be recognized according to their petrography and mineralogy. They were also independently classified into three arbitrary groups according to their petrography and mineralogy.

3.1.1. Lithic clasts of group I: Absence of anhydrous silicates

The lithic clasts of group I are the most common type; 37 clasts out of 64 studied belong to this group. They consist of magnetite, carbonates, and Fe,Ni-sulfides (average grain size <5 μm) set in a fine-grained, probably hydrated matrix (Fig. 4). No anhydrous silicates or metal grains were observed. There are large variations in modal abundances of magnetite and sulfide among the clasts (Fig. 4).

Magnetite is present in every lithic clast from group I. It occurs as framboids and platelets, either as isolated grains or in association with carbonates (Fig. 4b, d, and f). Sulfides are typically lath-shaped, Ni-poor pyrrhotite or troilite (Fig. 4e and f), occasionally coexisting with a Ni-rich sulfide (pentlandite?). Carbonates occur as isolated crystals (Fig. 4b) or as intergrowths with magnetite (Fig. 4d and f). In most lithic clasts of group I, dolomite [CaMg(CO₃)₂] is the main carbonate phase, although coexisting dolomite and magnesite ([Mg,Fe]CO₃) were found in one of the clasts (I4_LC6). The carbonate grains are texturally homogeneous and show no clear evidence of corrosion (Fig. 5). Clast I7_LC31 consists almost exclusively of magnesite (Fig. 4h). Petrographically, it is very different from any other lithic clasts.

3.1.2. Lithic clasts of group II: Presence of anhydrous silicates

Nineteen clasts among those studied belong to group II. They are characterized by the presence of anhydrous silicates embedded in a fine-grained, possibly hydrated matrix (Fig. 6). Fifteen clasts of group II contain magnetite, sulfides, and carbonates, with magnesite typically more abundant than dolomite. Opaque mineralogy is similar to that of group I clasts. In four clasts of group II, no carbonate grains were observed and magnesite is either rare or absent. The anhydrous silicates, ranging from ~1 to ~50 μm in size, consist of olivine, low-Ca and high-Ca pyroxenes, rare fragments of albitic plagioclase, and numerous cryptocrystalline microchondrules (<10 μm in diameter). A microCAI composed of spinel, perovskite and melilite was found in clast I4_LC8 (Fig. 6d). Several of the clasts of group II show evidence of brecciation.

3.1.3. Lithic clasts of group III: Absence of magnetite and presence of Fe,Ni-metal

The lithic clasts of group III are rare (8 out of 64 clasts studied). They are mainly composed of fine-grained matrix material and opaque minerals. Carbonates and anhydrous silicates are less abundant than in clasts of groups I and II. The opaque minerals consist of Fe,Ni-metal (~2 μm) and sulfides; magnesite is absent (Fig. 7). The sulfides and metal occur either as intergrowths or as isolated grains. Dolomite is the only carbonate present.

3.2. Chemical compositions of phyllosilicate-rich matrix, anhydrous silicates and carbonates

3.2.1. Phyllosilicate-rich matrix

Chemical compositions of fine-grained matrices in 23 clasts were measured by electron microprobe (9 of group I, 6 of group II, and 8 of group III). The group II lithic clasts studied are the ones containing opaque phases and carbonates. The average chemical compositions of the fine-grained matrices of the Isheyevo clasts have low totals ranging from ~80 to ~93 wt% (Table 1). The low totals of
the analyses and the mineralogy of the clasts described above suggest that the matrices are probably largely composed of phyllosilicates. Although high porosity of a sample may also result in low totals of the analyses, the Isheyev clasts appear to be rather compact (Figs. 4–7). To compare chemical compositions of the apparently hydrated matrices of the Isheyev clasts with those in CM and CI chondrites, we plotted our data on a diagram Si + Al–Fe–Mg together with the data reported by Bunch and Chang (1980) and Tomeoka and Buseck (1988) (Fig. 8). The analyses with
Fig. 5. BSE images of dolomite grains in Orgueil (CI chondrite, a) and in one of the group I lithic clast in the CB/CH-like Isheyevo chondrite (b). The textural differences may reveal different conditions or extent of the aqueous event. The white arrows point out the carbonate grain.

Fig. 6. BSE images of group II lithic clasts in Isheyevo. The Group II lithic clasts are characterized by the presence of anhydrous silicates (olivine and/or pyroxene, “sil.”) and are more or less enriched opaque minerals, as magnetite “mgt” (a and b). Group II clasts with the most-abundant opaque phases are also characterized by the presence of carbonate as magnesite “mag” (a). Fragments “frg” of silicates (c and f), microCAI (d), micro-crystalline chondrule with euhedral metal (e) were observed in the matrix “mx”. The microCAI is composed of spinel “sp” with a rim of melilite “mel” and a few inclusions of perovskite “pv”.
sulfur content higher than 6 wt%, probably due to electron beam overlap either with tochilinite or sub-μm-sized sulfides, were excluded. The phyllosilicate-rich matrices in the Isheyevo clasts appear to be mostly serpentine characterized by a large range of Fe/Mg ratio. They overlap in composition with phyllosilicates from CM and CR chondrites (Fig. 8) and are significantly different from the Orgueil matrix. There are no clear differences in chemical compositions of phyllosilicates from the lithic clasts of different groups (Fig. 8).

3.2.2. Anhydrous silicates

Some group II clasts are characterized by the presence of anhydrous silicate grains up to 50 μm in size (Fig. 6). Petrographically different types of fragments can be distinguished: some small spherical inclusions likely to be microchondrules, microCAIs (Fig. 6d), spherical silicates with euhedral metal inside (Fig. 6e), and larger fragments. Chemical compositions of anhydrous silicates fragments in 1_LC1, 18_LC100, 18_LC101, and 14_LC4 were measured by electron microprobe (Table 2). Microchondrules...
and larger fragments are composed of ferromagnesian olivine (Fa 2–57) and pyroxene (Fs 1–47, Wo <2). Petrographically, a link between these anhydrous silicates and the high-temperature components of metal-rich chondrites is suggested, as spherical silicate inclusions with euhedral metal are common in CH and Isheyevo chondrites (e.g., Krot et al., 2000; Ivanova et al., 2008). This is confirmed by the strong similarity in oxygen isotope compositions between the chondrules in Isheyevo and the chondrules and chondrule fragments in the clasts (Bonal et al., 2009).

### 3.2.3. Carbonates

The chemical compositions of 31 carbonate grains from 13 lithic clasts (10 from group I, 1 from group II, and 2 from group III) were measured by electron microprobe. Representative analyses are listed in Table 3. Several types of carbonates were identified: dolomite, magnesite [MgCO₃–FeCO₃ solid solution], and calcite [CaCO₃]. Calcite usually fills the cracks that crosscut the clasts and extend into the Isheyevo host. We infer that calcite probably resulted from terrestrial weathering. Both dolomite and magnesite have high MnO contents (1.4–4.8 wt%). The average chemical compositions of dolomite grains from the Isheyevo clasts and from Orgueil (Endress and Bishoff, 1996) are plotted in Fig. 9. The dolomite grains in Isheyevo are systematically enriched in FeO compared to those in Orgueil.

### 3.3. Structural order of polyaromatic carbonaceous matter

Raman spectra were acquired in situ in 48 lithic clasts present in the different lithologies of the Isheyevo meteorite. Each spectrum exhibits the so-called D- (~1350 cm⁻¹) and G-bands (~1580 cm⁻¹), indicating the presence of polyaromatic carbonaceous matter in all lithic clasts studied. In the case of opaque samples, like the samples studied here, Raman spectroscopy is a surface-analysis technique. In addition, the Raman efficiency of carbonaceous material is much higher than that of the silicates, oxides, carbonates, and sulfides – minerals dominant in matrix of the Isheyevo clasts. As a result, the Raman spectra of the Isheyevo clasts, as well as matrices of carbonaceous and ordinary chondrites considered here, show only D- and G-bands and no band due to the mineral phases.

Raman spectroscopy is highly sensitive to the structural order of polyaromatic carbonaceous matter. However, the
only structural parameter linked to the D- and G-bands spectral parameters is the lateral size of the basic structural units (e.g., Tuinstra and Koenig, 1970; Wopenka and Pasteris, 1993). The available relationship is highly inaccurate for poorly ordered polyaromatic carbonaceous matter. In particular, it cannot be used to quantitatively estimate the structural order of chondritic carbonaceous matter. Nevertheless, some spectral parameters are very sensitive to the structure of poorly ordered materials, even if they do not provide quantitative structural information. Raman spectroscopy can indeed easily identify a type 3 chondrite and some of the spectral parameters can be used to characterize its thermal history (e.g., Bonal et al., 2006, 2007a). On the other hand, Raman spectra of type 1 and 2 chondrites are characterized by the presence of an intense fluorescence background, preventing a precise spectral characterization. Therefore, it is not possible to distinguish a type 1 from a type 2 chondrite solely based on their Raman spectra, even if they experienced different thermal histories. Differences were observed in the Raman spectra of the Isheyevo clasts.

Table 3
Representative chemical compositions (in wt%) of carbonates present in lithic clasts of different groups.

<table>
<thead>
<tr>
<th>Clast</th>
<th>Gp</th>
<th>Mineral</th>
<th>CaO</th>
<th>MgO</th>
<th>MnO</th>
<th>FeO</th>
<th>CO₂</th>
<th>SiO₂</th>
<th>Cr₂O₃</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>I7_LC9</td>
<td>I</td>
<td>D</td>
<td>27.0</td>
<td>18.2</td>
<td>4.3</td>
<td>3.9</td>
<td>46.1</td>
<td>0.04</td>
<td>&lt;0.06</td>
<td>99.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>26.6</td>
<td>18.1</td>
<td>4.7</td>
<td>3.7</td>
<td>46.0</td>
<td>0.04</td>
<td>&lt;0.06</td>
<td>99.2</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>27.2</td>
<td>18.5</td>
<td>3.8</td>
<td>3.1</td>
<td>46.0</td>
<td>0.08</td>
<td>&lt;0.06</td>
<td>98.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>29.4</td>
<td>16.2</td>
<td>4.2</td>
<td>3.8</td>
<td>46.1</td>
<td>0.19</td>
<td>&lt;0.06</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>27.5</td>
<td>18.6</td>
<td>3.2</td>
<td>3.8</td>
<td>46.4</td>
<td>0.13</td>
<td>&lt;0.06</td>
<td>99.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>28.7</td>
<td>17.3</td>
<td>2.2</td>
<td>4.8</td>
<td>47.1</td>
<td>0.91</td>
<td>&lt;0.06</td>
<td>101.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>33.0</td>
<td>14.1</td>
<td>2.8</td>
<td>4.1</td>
<td>46.0</td>
<td>0.30</td>
<td>&lt;0.06</td>
<td>100.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>26.5</td>
<td>17.8</td>
<td>4.8</td>
<td>4.2</td>
<td>46.0</td>
<td>0.25</td>
<td>0.06</td>
<td>99.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>29.5</td>
<td>16.2</td>
<td>2.8</td>
<td>4.5</td>
<td>46.1</td>
<td>0.48</td>
<td>&lt;0.06</td>
<td>99.6</td>
<td></td>
</tr>
<tr>
<td>I4_LC4</td>
<td>II</td>
<td>M</td>
<td>0.6</td>
<td>25.7</td>
<td>4.4</td>
<td>24.4</td>
<td>46.4</td>
<td>0.14</td>
<td>&lt;0.06</td>
<td>101.7</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>0.8</td>
<td>26.7</td>
<td>4.2</td>
<td>23.6</td>
<td>46.6</td>
<td>0.10</td>
<td>&lt;0.06</td>
<td>102.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>0.7</td>
<td>26.2</td>
<td>3.9</td>
<td>24.2</td>
<td>46.5</td>
<td>0.07</td>
<td>&lt;0.06</td>
<td>101.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>0.7</td>
<td>25.9</td>
<td>3.9</td>
<td>24.1</td>
<td>46.5</td>
<td>0.30</td>
<td>&lt;0.06</td>
<td>101.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>1.5</td>
<td>24.6</td>
<td>4.5</td>
<td>24.3</td>
<td>46.8</td>
<td>0.62</td>
<td>0.11</td>
<td>102.5</td>
<td></td>
</tr>
<tr>
<td>I7_LC3</td>
<td>III</td>
<td>D</td>
<td>27.5</td>
<td>18.6</td>
<td>1.8</td>
<td>5.2</td>
<td>46.6</td>
<td>0.24</td>
<td>&lt;0.06</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>28.2</td>
<td>17.9</td>
<td>1.4</td>
<td>5.7</td>
<td>46.4</td>
<td>0.19</td>
<td>&lt;0.06</td>
<td>99.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>27.6</td>
<td>18.5</td>
<td>1.7</td>
<td>4.9</td>
<td>46.1</td>
<td>0.07</td>
<td>&lt;0.06</td>
<td>99.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>28.4</td>
<td>17.3</td>
<td>1.8</td>
<td>5.1</td>
<td>45.6</td>
<td>0.17</td>
<td>&lt;0.06</td>
<td>98.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>29.1</td>
<td>17.7</td>
<td>1.5</td>
<td>5.1</td>
<td>46.3</td>
<td>0.08</td>
<td>&lt;0.06</td>
<td>99.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>28.1</td>
<td>18.1</td>
<td>1.4</td>
<td>5.3</td>
<td>46.0</td>
<td>0.05</td>
<td>&lt;0.06</td>
<td>98.9</td>
<td></td>
</tr>
</tbody>
</table>

Gp, petrographic group as defined in the text; D, dolomite; M, magnesite (MgCO₃–FeCO₃ solid solution).

Fig. 9. FeO–CaO–MgO (wt%) ternary diagram showing composition of dolomites in the CB/CH-like Isheyevo chondrite. Compositions of dolomites in CI chondrites (Orgueil, Alais, Ivuna) are given for comparison (data from Endress and Bishoff, 1996). Black squares stand for Isheyevo, grey diamonds for CI chondrites. Each point represents the chemical composition of a separate carbonate grain.
We divided them into two groups: those with Raman spectra similar to (i) type 1 and type 2 chondrites (group “a”), and (ii) to type 3 chondrites (group “b”).

In Fig. 10a and b we show the raw Raman spectra of lithic clasts I4_LC16 (group “a”) and I7_LC30 (group “b”). To remove the effects of the fluorescence background and to facilitate comparison of the D- and G-bands between the two classes, we plot the same data after the intensity at 800 cm\(^{-1}\) was arbitrarily set to zero and the spectra were normalized to the intensity of the G-band in Fig. 10c and d. Although the fluorescence background is variable among the Raman spectra within an individual clast of group “a” (Fig. 10a), Raman features such as the width, position, and relative intensity of the D- and G-bands are relatively reproducible (Fig. 10c). The Raman spectra within an individual clast of group “b” (Fig. 10b) are also reproducible (Fig. 10d), implying that the organic material in each clast is relatively homogeneous. This justifies averaging the Raman spectra for each lithic clast. The average spectra for the clasts studied are plotted in Fig. 11.

A large majority of the lithic clasts (38 out of 48) is characterized by average Raman spectra with broad D- and G-bands, superimposed onto a variable fluorescence background (group “a”, Fig. 11a). Fig. 11b shows the same spectra after background subtraction (intensity arbitrarily set to zero at 800 cm\(^{-1}\)) and normalization to the intensity of the G-band. The D- and G-bands are poorly defined, and the spectral valley between the two bands is very shallow. These spectra are typical for poorly organized polyaromatic carbonaceous matter such as that present in Orgueil (CI) and Renazzo (CR2) (Fig. 11b).

A second group of lithic clasts is rare (10 out of 48) and is characterized by well-defined Raman bands (group “b”, Fig. 11c and d). Compared to group “a”, the D- and G-bands are narrower, and the spectral valley between the D- and G-bands is better defined. This group can be further

![Fig. 10. Raman spectra of two representative lithic clasts in the CB/CH-like Isheyevo chondrite (a–d). The D- (\sim 1350 cm\(^{-1}\)) and G-bands (\sim 1580 cm\(^{-1}\)) are systematically present, attesting the presence of polyaromatic carbonaceous matter in each of the lithic clasts. Two main groups can be distinguished amongst the lithic clasts according to their Raman spectra: 1) group “a”: spectra with a fluorescence background (a) and very broad D- and G-bands (c); 2) group “b”: spectra without fluorescence background (b) and D- and G-bands nicely defined in comparison to group “a” (d).](image-url)
Fig. 11. Average Raman spectra of the lithic clasts in the CB/CH-like Isheyevo chondrite. A majority of lithic clasts is characterized by a high fluorescence background and broad D- and G-bands (a); a minority of spectra is characterized by a low fluorescence background and/or well-defined D- and G-bands (c and d). Background corrected and normalized average spectra reveal the same groups as the raw data: a majority with a small spectral valley between D- and G-bands and with a positive-slope baseline (b), comparable to types 1 or 2 chondrites; a minority with well-defined D- and G-bands (e), comparable to type 3.0 chondrites. Average Raman spectra of Orgueil, Renazzo and Semarkona are shown for reference (thick black spectra).
subdivided into two subgroups, “b1” and “b2”. Six lithic clasts are characterized by a low fluorescence background (subgroup “b1”, Fig. 11c; note expanded Y-axis). The remaining four lithic clasts (subgroup “b2”) have a non-negligible fluorescence background (Fig. 11d). However, that background does not significantly distort the spectra and the G-band is clearly narrower than in group “a” spectra. The average (Fig. 11c and d) and normalized (Fig. 11e) Raman spectra of these 10 lithic clasts (“b1” and “b2”) are characterized by an easily visible spectral valley between the D- and G-bands and a baseline that is either not disturbed or only slightly disturbed. These spectra are typical for slightly organized polyaromatic carbonaceous matter as present in Semarkona (LL3.0).

Spectral parameters of the D- and G-bands for the Raman spectra of the group “b” have been determined with the same method used by Bonal et al. (2006, 2007a). The full width at half maximum of the D-band (FWHM-D) and its intensity relative to the G-band (I_D/I_G) have proven to be the most sensitive spectral parameters to the degree of ordering of polyaromatic carbonaceous matter in type 3 chondrites. A comparison of these spectral parameters (Fig. 12) shows that the degree of ordering is variable from clast to clast and covers the range between Semarkona (LL3.0) and ALHA 77307 (CO 3.05). The spectral parameters of group “b1” are well aligned with the trend defined by the reference chondrites. On the other hand, the parameters from the group “b2” are shifted to the left of this trend.

### 3.4. Oxygen isotopic composition of carbonates

The Isheyevo carbonates large enough for SIMS measurements are mainly from group I lithic clasts. One measured carbonate grain is from the group II clast I4_LC4 (Fig. 6a). The oxygen isotopic compositions of carbonates in the Isheyevo lithic clasts are listed in Table 4 and compared with the data for carbonates from other chondrite groups on an oxygen three-isotope diagram (Fig. 13). In Fig. 14, the same data are plotted as $D^{17}O$ vs. $D^{18}O$, where $D^{17}O = \delta^{17}O + 0.52 \times \delta^{18}O$.

**Table 4** Oxygen isotopic composition of carbonates in Isheyevo clasts measured in situ using the UH Cameca ims-1280.

<table>
<thead>
<tr>
<th>Clast</th>
<th>Gp</th>
<th>n°</th>
<th>Mineral</th>
<th>$\delta^{18}O$</th>
<th>$2\sigma$</th>
<th>$\delta^{17}O$</th>
<th>$2\sigma$</th>
<th>$D^{17}O$</th>
<th>$2\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>17_LC31</td>
<td>I</td>
<td>1</td>
<td>Magnesite</td>
<td>29.7</td>
<td>1.0</td>
<td>16.9</td>
<td>0.95</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28.9</td>
<td>1.0</td>
<td>16.2</td>
<td>0.96</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>14_LC2</td>
<td>I</td>
<td>2</td>
<td>Dolomite</td>
<td>29.9</td>
<td>1.0</td>
<td>16.2</td>
<td>1.0</td>
<td>0.63</td>
<td>1.2</td>
</tr>
<tr>
<td>14_LC6</td>
<td>I</td>
<td>3</td>
<td>Magnesite</td>
<td>27.4</td>
<td>1.1</td>
<td>14.3</td>
<td>1.0</td>
<td>0.02</td>
<td>1.2</td>
</tr>
<tr>
<td>14_LC4</td>
<td>II</td>
<td>4</td>
<td>Magnesite</td>
<td>26.1</td>
<td>1.1</td>
<td>13.7</td>
<td>1.0</td>
<td>0.09</td>
<td>1.2</td>
</tr>
<tr>
<td>14_LC3</td>
<td>II</td>
<td>5</td>
<td>Dolomite</td>
<td>26.0</td>
<td>0.97</td>
<td>12.9</td>
<td>1.1</td>
<td>-0.6</td>
<td>1.2</td>
</tr>
<tr>
<td>14_LC14</td>
<td>I</td>
<td>6</td>
<td>Dolomite</td>
<td>26.3</td>
<td>1.0</td>
<td>13.0</td>
<td>1.1</td>
<td>-0.7</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Magnesite</td>
<td>28.6</td>
<td>1.1</td>
<td>13.8</td>
<td>1.1</td>
<td>-1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>15_LC1</td>
<td>I</td>
<td>7</td>
<td>Dolomite</td>
<td>30.0</td>
<td>0.50</td>
<td>14.2</td>
<td>0.82</td>
<td>-1.4</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>32.2</td>
<td>0.59</td>
<td>14.6</td>
<td>0.77</td>
<td>-2.2</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Gp, petrographic group as defined in the text; n°, reference number used in Figs. 13 and 14.
The $\delta^{17}$O values of carbonates from seven clasts range from $-2.2^{\circ}$ to $1.4^{\circ}$ (Table 4; Fig. 14). The compositions differ by more than the experimental uncertainties and span the range covered by carbonates in Tagish Lake, Orgueil, and the CM chondrites. Two different carbonate grains were measured in the lithic clasts I4_LC14 (#6 in Figs. 13 and 14) and I5_LC1 (#7 in Figs. 13 and 14). In both cases, the $\Delta^{17}$O values obtained for carbonates in an individual clast are within experimental uncertainty of each other. Two spots analyzed in a large magnesite grain from the lithic clast I7_LC31 (#1 in Figs. 13 and 14) showed similar compositions.

4. DISCUSSION

Based on mineralogy, we divided the Isheyevo clasts into three groups: totally hydrated (group I), with anhydrous silicates (group II), and magnetite-free, Fe,Ni-metal-bearing clasts (group III). Based on the Raman characteristics of the polyaromatic carbonaceous matter present in the clasts, we divided them into two groups: those with poorly organized polyaromatic carbonaceous matter (group “a”), comparable to types 1 and 2 chondrites) and those with slightly organized polyaromatic carbonaceous matter (group “b” composed of subgroups “b1” and “b2”, comparable to type 3 chondrites). The vast majority of the group I clasts (34 of 36 studied) contains poorly organized polyaromatic carbonaceous matter (group “a”). Only two lithic clasts of group I contain polyaromatic carbonaceous matter that is more ordered (group “b2”). Like in lithic clasts of group I, most clasts of group II contain poorly organized polyaromatic carbonaceous matter (group “a”). Only two out of 19 group II clasts contain more ordered

Fig. 13. Three-isotope plot of $\delta^{17}$O vs. $\delta^{18}$O relative to SMOW illustrating the isotopic variability of carbonates (squares: dolomite; diamonds: magnesite) in the lithic clasts in the CB/CH-like Isheyevo chondrite (error bars = 2$\sigma$). The terrestrial fractionation line (TFL) is shown for reference. The grey areas show carbonates from Orgueil, Tagish Lake and CM2 chondrites (data from Benedix et al., 2003; Leshin et al., 2001). Numbers denote different lithic clasts listed in Table 5.

Fig. 14. $\Delta^{17}$O vs. $\delta^{18}$O of carbonates in CM2 chondrites (open circles) and lithic clasts of the CB/CH-like Isheyevo chondrite (squares: dolomite; diamonds: magnesite). The lithic clast numbers (1–7) are defined in Table 5. The oxygen isotopic compositions of carbonates from CM2 chondrites (high yield data only from Benedix et al., 2003) show a positive correlation between $\Delta^{17}$O and $\delta^{18}$O. Data for the Isheyevo carbonates do not follow this correlation. Error bars are 2$\sigma$. 
polyaromatic carbonaceous matter comparable to type 2 chondrites (group “b2”). In contrast, the polyaromatic carbonaceous matter in group III clasts is systematically more ordered (group “b1”) and is comparable with organic matter in ordinary and carbonaceous chondrites of petrologic type 3.00–3.05. The main characteristics of the three groups of clasts are summarized in Table 5.

In the following discussion, we will show that the lithic clasts from Isheyevo exhibit a wide diversity of characteristics, even within one group. Much of the diversity appears to reflect variations in their aqueous alteration and thermal metamorphic history. It could be a result of sampling of either different portions of a single parent body that experienced alteration and thermal metamorphism to varying degrees, or sampling of multiple parent bodies. The diversity among the clasts may be sufficiently large to exclude an origin from a single body. We will also compare the characteristics of the Isheyevo clasts to those of aqueously altered meteorites such as CI, CM, and CR chondrites and to aqueously altered chondritic clasts present in different meteorites. Brief discussions of the nature of the parent body(ies) of the clasts will follow, as well as suggested measurements to constrain their origin and time of incorporation into the Isheyevo parent asteroid.

4.1. The diversity of the Isheyevo clasts and comparisons with known meteorite types

4.1.1. Mineralogy and petrology

4.1.1.1. Comparison to hydrated chondrite groups: CI, CM, and CR. The diversity among Isheyevo clasts (Table 5) indicates a variety of formation environments and a range of secondary histories. Here we will discuss how the characteristics of the clasts compare to those of aqueously altered CI, CM, and CR chondrites and the unusual CI/CM chondrite Tagish Lake.

Group I Isheyevo clasts and CI chondrites are similar in that they are composed almost entirely of fine-grained, aqueously altered material. The mineralogy of the Isheyevo lithic clasts has some similarities with CI chondrites, but there are also distinct differences. A wide variety of magne-

<table>
<thead>
<tr>
<th>Petrographic characteristics</th>
<th>Thermal history</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group I</td>
<td>Totally hydrated – variable abundances of sulfate, magnetite – no metal – dolomite is the main carbonate</td>
<td>Comparable to types 1, 2 chondrites with only a few exceptions</td>
</tr>
<tr>
<td>Group II</td>
<td>Presence of several-microns-sized anhydrous silicates – magnesite more common than dolomite</td>
<td>Comparable to types 1, 2 chondrites with only a few exceptions</td>
</tr>
<tr>
<td>Group III</td>
<td>No magnetite – presence of metal grains – dolomite as the main carbonate</td>
<td>Comparable to types 3.0 – 3.05 chondrites</td>
</tr>
</tbody>
</table>

* Only 4/19 where carbonates and magnetite are rare and anhydrous silicates are larger.

and Prinz, 1993; Riciputi et al., 1994; Endress and Bishoff, 1996). Dolomite is the dominant carbonate, breunnerite is much less abundant, and calcite is very rare. The dominant carbonate in Isheyevo clasts is dolomite, but dolomites in Isheyevo are enriched in FeO compared to those in CI chondrites (Fig. 9). In addition, dolomite grains in Isheyevo commonly occur as isolated grains that are texturally homogeneous and do not show evidence of corrosion (Fig. 5). In contrast, dolomite grains in Orgueil tend to be corroded and fractured, and are commonly intergrown with other aqueously formed minerals (Fig. 5). Phyllosilicates in Isheyevo clasts are significantly different in chemical compositions from the Orgueil matrix (Fig. 8). Indeed, Orgueil is composed of serpentine–saponite intergrowths, with serpentine and saponite present in approximately equal abundances (e.g., Tomeoka and Buseck, 1988). The phyllosilicate-rich matrices of the Isheyevo clasts cluster along the serpentine solid solution line. The differences in carbonate mineralogy and morphology and in the phyllosilicate composition suggest that the physico-chemical conditions of aqueous alteration in CI chondrites and Isheyevo clasts were distinct.

There are significant mineralogical differences between the CM2 chondrites and the Isheyevo clasts. The framboi,

dients from the Orgueil matrix (Fig. 8). Indeed, Orgueil is composed of serpentine–saponite intergrowths, with serpen-
tine and saponite present in approximately equal abundances (e.g., Tomeoka and Buseck, 1988). The phyllosilicate-rich matrices of the Isheyevo clasts cluster along the serpentine solid solution line. The differences in carbonate mineralogy and morphology and in the phyllosilicate composition suggest that the physico-chemical conditions of aqueous alteration in CI chondrites and Isheyevo clasts were distinct.

and Prinz, 1993; Riciputi et al., 1994; Endress and Bishoff, 1996). Dolomite is the dominant carbonate, breunnerite is much less abundant, and calcite is very rare. The dominant carbonate in Isheyevo clasts is dolomite, but dolomites in Isheyevo are enriched in FeO compared to those in CI chondrites (Fig. 9). In addition, dolomite grains in Isheyevo commonly occur as isolated grains that are texturally homogeneous and do not show evidence of corrosion (Fig. 5). In contrast, dolomite grains in Orgueil tend to be corroded and fractured, and are commonly intergrown with other aqueously formed minerals (Fig. 5). Phyllosilicates in Isheyevo clasts are significantly different in chemical compositions from the Orgueil matrix (Fig. 8). Indeed, Orgueil is composed of serpentine–saponite intergrowths, with serpentine and saponite present in approximately equal abundances (e.g., Tomeoka and Buseck, 1988). The phyllosilicate-rich matrices of the Isheyevo clasts cluster along the serpentine solid solution line. The differences in carbonate mineralogy and morphology and in the phyllosilicate composition suggest that the physico-chemical conditions of aqueous alteration in CI chondrites and Isheyevo clasts were distinct.

There are significant mineralogical differences between the CM2 chondrites and the Isheyevo clasts. The fram-

boids, spherules, and platelets that are common magnetite morphologies in Isheyevo clasts are rare in CM2 chondrites (e.g., Brearley and Jones, 1998). The dominant carbonate in CM chondrites is calcite (Johnson and Prinz, 1993; Riciputi et al., 1994; Benedix et al., 2003), not dolomite as in Isheyevo clasts. CM2 chondrites also contain 30–50% anhydrous minerals in the form of chondrules and CAIs. Only the group II Isheyevo clasts have anhydrous silicates. In CM2 chondrites, the anhydrous silicates show clear evidence of having experienced aqueous alteration that produced the matrix mineralogy (e.g., Brearley and Jones, 1998 and references therein). However, in Isheyevo, the anhydrous silicates do not show clear evidence of aqueous alteration. These differences indicate that the Isheyevo clasts and CM2 chondrites are not closely related.

CR2 chondrites show clear evidence of aqueous alteration, but these meteorites bear little resemblance with the Isheyevo clasts. The most obvious difference is the high abundance of chondrules, metal, troilite and CAIs (up to 70% of the rock). The size and abundance of anhydrous silicates and metal in Isheyevo clasts are much smaller than in CR2 chondrites. The mineralogy is somewhat similar to the clasts. Both Isheyevo and CR2 chondrites are dominated by serpentine, but the composition differ
systematically between the two types of material (Fig. 8). The dominant carbonate in the matrix CR2 chondrites is calcite rather than dolomite as in Isheyevo clasts.

Tagish Lake is an unusual carbonaceous chondrite with chemical and mineralogical similarities to CI and CM chondrites. Two main lithologies were identified: a dominant carbonate-poor lithology and a less-abundant carbonate-rich lithology (e.g., Zolensky et al., 2002). The matrix of the carbonate-poor lithology consists mainly of saponite, serpentine and Fe,Ni-sulfides. Isolated olivine grains are common and Ca-carbonates dominate the rare carbonates (Zolensky et al., 2002). These two last characteristics show that the Isheyevo clasts did not sample the same parent body as the carbonate-poor lithology of Tagish Lake. The phyllosilicates in the carbonate-rich lithology consist almost entirely of saponite (Zolensky et al., 2002). Phyllosilicates in Isheyevo clasts are distributed along the serpentine solid solution line. Thus, Isheyevo clasts sampled a different parent body that the carbonate-rich lithology of Tagish Lake.

While there are similarities between the Isheyevo clasts and CI and the matrices of CM and CR chondrites, on the whole, the characteristics of the clasts do not match those of any of these meteorite classes. The observations summarized above show that the Isheyevo lithic clasts are not fragments of the CI, CM, CR, or Tagish Lake parent bodies.

4.1.1.2. Comparison to aqueously altered chondritic clasts present in other meteorites. Carbonaceous chondritic clasts have been reported in a variety of regolith breccias including unequilibrated ordinary chondrites (e.g., Bischoff et al., 2006), carbonaceous chondrites (e.g., Johnson et al., 1990; Weisberg et al., 1993) and, achondrites (e.g., Zolensky et al., 1996). These clasts can provide critical information about the variety of primitive materials in the early Solar System, interactions between different classes of asteroids and the processes affecting them. The clasts identified in other meteorites were generally considered to be CI- and C2-like similar to CR and CM chondrites, although materials that do not appear to have analogues in other meteorites were also observed (e.g., Zolensky et al., 1996; Zolensky and Ivanov, 2003). However, due to the small sizes of the clasts, mainly mineralogical and petrological criteria have been considered, and further analyses were not always possible. A systematic survey of the clasts present in a large suite of meteorites is underway by Zolensky et al. (2009). This will undoubtedly place tighter constraints on the parent bodies sampled by the clasts present in diverse meteorites. Below we briefly summarize the characteristics of clasts that have been described in some detail from several classes of meteorites and compare them to the Isheyevo clasts.

CM2 clasts are relatively common in the HED meteorites (e.g., Zolensky et al., 1996 and references therein). They are identified by textures, mineralogy, mineral chemistry and bulk compositions. A lesser proportion of clasts in HEDs comes from CR2 chondrites, and other rare types are present (Zolensky et al., 1996). We previously showed that, despite some similarities, the Isheyevo clasts are different from CM and CR chondrites. Hence, they are different from the clasts in HED meteorites.

The Cumberland Falls aubrite contains numerous chondritic inclusions. But these inclusions contain chondrules and metal grains and have textures of unequilibrated ordinary chondrites (e.g., Neal and Lipschutz, 1981). Although the clasts in Cumberland Falls are probably not samples of the major chondrite groups (Lipschutz et al., 1988), they are quite distinct from the Isheyevo clasts.

Chondritic clasts are common in CV3 chondrites (e.g., Johnson et al., 1990). Based on petrologic, chemical and oxygen isotopic data it was shown that the clasts present in CV3 chondrites comprise a petrographic sequence ranging from a type which contains chondrules and refractory inclusions and resembles CV3 or CO3 chondrites to a type which contains porous aggregates of iron-rich olivines. CV3 or CO3 chondrites are dominated by high-temperature components such as chondrules and CAIs and their matrices consist of Fe-rich olivine and clinoxyroxene (e.g., Brearley and Jones, 1998). Hence, the Isheyevo clasts are not like CV and CO chondrites or like the clasts they contain.

CR2 chondrites are characterized by the presence of numerous chondritic clasts, which are texturally and mineralogically similar to the matrix of CR2 chondrites. Their petrographic features and bulk major element compositions are essentially identical to those in CR2 chondrites. Weisberg et al. (1993) considered CR2 clasts and matrix to be the same material. They thus differ from the Isheyevo clasts.

A large number of ordinary chondrites are brecciated. Xenolithic clasts are minor in comparison to cognate clasts (Bischoff et al., 2006 and references therein). Indeed, each group (H, L, LL) is dominated by lithic fragments of its respective compositional group, frequently of varying petrologic grade and embedded into finer-grained, often less equilibrated material of ordinary chondrite parentage (Keil, 1982). Some CM-like clasts were recognized in a few ordinary chondrites as Dimmit (Bischoff et al., 2006). The Isheyevo clasts do not resemble the ordinary chondrites, which are dominated by high-temperature components such as chondrules and CAIs. Nor do they resemble the matrix or the lithic clasts of ordinary chondrites. Indeed, in most unequilibrated ordinary chondrites the chondrule rims and matrix are composed of densely packed olivine (e.g., Brearley and Jones, 1998, and references therein), and smectite is the dominant phase in Semarkona matrix (Alexander et al., 1989), unlike the Isheyevo clasts.

In summary, the Isheyevo clasts are different from the clasts identified in CR chondrites, CV chondrites, ordinary chondrites and HED achondrites.

4.1.1.3. Comparison to the anomalous chondrite, Kaidun. Some chondrites do not fit into the classic classification scheme. Such meteorites are called “anomalous”. An example is the Kaidun breccia. Zolensky and Ivanov (2003) gave detailed petrologic description of Kaidun and some of its clasts. MacPherson et al. (2009) focused on the trace element and O isotopes chemistry. Accordingly Kaidun appears to be particularly complex, as it contains an unprecedented accumulation of materials from different parent bodies, principally carbonaceous and enstatite chondrites. Indeed, CV3, CM2, EH3-5, EL3 and also R
lithologies were identified in Kaidun, as well as unique alkali-enriched clasts, phosphide-bearing clasts and also Ca-rich achondrite materials (e.g., Zolensky and Ivanov, 2003; MacPherson et al., 2009). These lithologies are not related to any clasts present in Isheyevo. So-called CM1 and new C1- and C2-type lithologies were also recognized in Kaidun (e.g., Zolensky and Ivanov, 2003; MacPherson et al., 2009). They could potentially have sampled the same parent bodies as the clasts in Isheyevo and are the lithologies of interest in here.

The so-called CM1-A lithology experienced extensive aqueous alteration. It is characterized by the presence of abundant magnetite and absence of olivine, glass, or objects that can be unambiguously called chondrules (Zolensky and Ivanov, 2003). The CM1-A lithology in Kaidun is also characterized by very abundant pyrrhotite, and calcite is the most common carbonate. In the aqueously altered group I Isheyevo clasts, pyrrhotite is a minor phase and dolomite is more common than calcite, excluding a common origin.

The C1 lithology in Kaidun consists of fine-grained serpentine, with very abundant pyrrhotite and pentlandite, and with scattered larger crystals of anhydrous silicates. The presence of residual olivine and pyroxene shows that alteration was far from complete. In that respect, the C2-A lithology would be comparable with group II Isheyevo clasts. However, no chondrules or fragments of chondrules were observed in the C2-A lithology in Kaidun. Moreover, sulfide is a minor phase in group II clasts in Isheyevo. Hence the C2-A lithology in Kaidun and Isheyevo clasts did not sample the same parent body.

The C2-B lithology in Kaidun is made of fine-grained matrix of serpentine, olivine, low-Ca pyroxene, pyrrhotite, and Ca-carbonate. No large crystals or chondrule fragments were observed. This lithology can then only be compared with groups I and III clasts in Isheyevo. Nevertheless, Ca-carbonates are rare, and Ni-rich sulfides are a minor phase in Isheyevo clasts, unlike in the Kaidun C2-B lithology.

4.1.2. Variations in metamorphic history

4.1.2.1. Thermal history of Isheyevo clasts. The lithic clasts in Isheyevo appear to have experienced a variety of thermal histories, as reflected in their mineralogy and the structure of the polyaromatic carbonaceous matter they contain. The petrographic observations reported by Ivanova et al. (2008) indicate that the Isheyevo meteorite largely escaped thermal metamorphism, but experienced shock metamorphism of stage S4 as revealed by the presence of melt veins and planar fractures of olivine grains. However, the clasts do not exhibit clear indications of shock. The characteristics of the clasts reflect the superposition of the pre-accretionary history of the material that became the clasts, the conditions on the parent bodies where they formed, and the accretion and shock history of the Isheyevo parent body.

The majority of clasts of groups I and II (51 out of 56) contain polyaromatic carbonaceous matter that is poorly organized, similar to that in CI, CM, and CR chondrites. The lack of evidence for dehydration (e.g., low totals of electron microprobe analyses of the fine-grained matrices of the clasts; Table 1) and the presence of poorly organized polyaromatic carbonaceous matter in these clasts indicate that they were not heated above \( \sim \)150 °C (by analogy with CI and CM chondrites; Clayton and Mayeda, 1984; Zolensky et al., 1989; Guo and Eiler, 2007), either before or after incorporation into the Isheyevo parent body.

The lithic clasts of group III have fine-grained matrices that have apparently been aequously altered, but lack magnetite grains; Fe,Ni-metal is present instead. The polyaromatic carbonaceous matter is systematically more organized than that in lithic clasts of group I and II, comparable with the degree of ordering of organic matter in type 3.00–3.05 chondrites. On a diagram FWHM-D (full width at half maximum of the D-band) vs. I_D/I_G (ratio of intensities of D- and G-bands), the Raman parameters for these four clasts do not fall on the metamorphic trend defined by the group III clasts and type 3 chondrites (Fig. 12). These observations suggest that the precursor and the metamorphic history of the organic material in the group III Isheyevo lithic clasts and those in the matrices of type 3 chondrites were very similar (e.g., Bonal et al., 2006, 2007a).

There are four lithic clasts of groups I and II with a somewhat more organized polyaromatic carbonaceous matter than in the majority of groups I and II clasts (group “b2”). The Raman parameters for these four clasts do not fall on the metamorphic trend defined by the group III lithic clasts and type 3 chondrites (Fig. 12). This may reflect either differences in the organic precursors or different metamorphic histories experienced by these clasts. Organic material with similar characteristics has not been observed among CO3, CV3, and unequilibrated ordinary chondrites (Quirico et al., 2003; Bonal et al., 2006, 2007a).

The Isheyevo meteorite experienced a high level of shock metamorphism. Thus the lithic clasts could have experienced some shock metamorphism, if they accreted prior to or contemporaneously with the shock event(s). However, as underlined earlier, no mineralogical or textural evidences of shock effects were recognized within the lithic
clasts studied. Moreover, within a given clast, the structure of the organic material is essentially the same throughout. Shock can be very non-uniform in its effects since it is amplified or diminished depending on the material properties and morphologies. Hence, if the clasts had experienced shock metamorphism, we would expect the structural order of the polyaromatic carbonaceous matter to be highly heterogeneous at the micron scale. Instead we only observe small differences between the Raman spectra within a clast (Fig. 10a and c) that can be attributed to primary heterogeneity, which is common in natural, unshocked samples (e.g., Orgueil).

We conclude that the degree of ordering of the polyaromatic carbonaceous matter reflects the thermal history of the lithic clast before incorporation into the Isheyevo parent body.

4.1.2.2. Comparison to metamorphosed CM chondrites. Based on mineralogy, volatile element concentrations, and reflectance spectra, it has been inferred that some hydrated carbonaceous chondrites experienced thermal metamorphism (e.g., Tomoeoka et al., 1989a,b; Tomeoka, 1990; Bischoff and Metzler, 1991; Ikeda, 1992; Nakamura, 2005). Among them, the CM-type is dominant (Nakamura, 2005). In contrast to unheated chondrites (CI, CM, CR), these meteorites (e.g., Belgica-7904, Yamato-86720, Yamato-82162, Dhofar-225) experienced aqueous alteration followed by heating at elevated temperatures with corresponding phyllosilicate dehydration (e.g., Ikeda and Prinz, 1993; Nakamura, 2005). Group III clasts in Isheyevo, having experienced some thermal metamorphism, could potentially be related to these heated and aqueously altered carbonaceous chondrites.

Based on data from synchrotron X-ray diffraction analysis of the matrix, heated hydrated carbonaceous chondrites have been classified as stage I (very weakly heated) to stage IV (strongly heated). The temperature estimates for dehydration are: stage I (< 300 °C), stage II (300–500 °C), stage III (500–750 °C), and stage IV (> 750 °C) (Nakamura, 2005). As shown in the previous section, the structural order of the polyaromatic carbonaceous matter present in group III clasts is comparable to 3.0–3.05 ordinary chondrites. The metamorphic temperatures of the chondrites with the lowest petrologic types are not irrevocably established. However, 300 °C appears to be an upper limit for 3.0–3.05 clasts (e.g., Huss et al., 2006). Hence, group III clasts are different from metamorphosed CM chondrites of stages II to IV. Moreover, stage I samples do not show heat-induced mineralogical changes, because they were heated only slightly. Stage I CM chondrites can hardly be distinguished from unheated CM chondrites (Nakamura, 2005). As we already showed, Isheyevo clasts are distinct from unheated CM chondrites. Thus, Isheyevo clasts and metamorphosed CM chondrites sampled different parent bodies.

4.1.3. Oxygen isotopic compositions of carbonates

Variations in oxygen isotopic composition of solar system materials result from a combination of two general processes: (1) mass-dependant isotope fractionation, which is particularly large during hydration at low temperatures and (2) interaction between isotopically distinct reservoirs through mixing and exchange. The combination of these two processes has left each meteorite parent body with distinct oxygen isotopic composition. Therefore oxygen isotopic compositions are used to classify chondrites and can help to identify a possible genetic relationship between the various carbonaceous chondrites and their components. Oxygen isotopes can also help to constrain the conditions of chemical processes occurring in the nebula and on the chondrite parent bodies (e.g., Clayton and Mayeda, 1999).

Two major classes of models have been proposed to describe the effects of aqueous alteration on oxygen isotopic compositions of carbonaceous chondrites: a closed-system alteration model (Clayton and Mayeda, 1984, 1999) and a fluid-flow model (Young et al., 1999; Young, 2001). The initial oxygen isotopic composition of water on the chondrite parent asteroids is not known, but is presumed to be 18O-depleted relative to the solids. In both models, the oxygen isotopic composition of the fluid evolves in response to continued exchange with the host rock. According to the closed-system alteration model, variations in oxygen isotopic compositions among CI, CM chondrites can be explained by differences in the water/rock ratio and temperature of aqueous alteration. The resulting rock is homogeneous. According to the fluid-flow model, degree of alteration and the composition of the resulting minerals reflect the details of fluid passage through the rock. Some areas may be heavily altered, while others may have largely escaped alteration. In both models, different Δ17O values would be expected for different conditions of aqueous alteration (e.g., on different parent bodies), and the fluid-flow model would predict a range in Δ17O values in a single parent body.

Fig. 13 shows the ranges of oxygen isotopic compositions of carbonates in Orgueil (CI), several CM chondrites, and Tagish Lake. There are systematic differences in Δ17O values for carbonates in these chondrite groups: Orgueil: +0.42‰ to +0.51‰ (Leshin et al., 2001); CMs: −0.67‰ to −1.02‰ (Benedix et al., 2003), and Tagish Lake: +1.42‰ to +1.98‰ (Leshin et al., 2001). The Δ17O values of carbonates in six Isheyevo lithic clasts of group I range from −2.2‰ to +1.3‰. The only carbonate grain measured in a clast of group II has Δ17O of ~+0.1‰. The spread in the Δ17O values is well outside of the measurement errors. The range in Δ17O values of carbonates in the Isheyevo clasts of group I is similar to the entire range of Δ17O values of carbonates in Orgueil, CMs, and Tagish Lake combined. The large range in oxygen isotopic compositions of carbonates in the Isheyevo clasts implies that these carbonates precipitated from fluids of different isotopic composition. This may reflect either evolution of oxygen isotopic composition of a fluid on a single parent body, as a result of water-rock interaction, or sampling of different parent bodies having different isotopic compositions of fluids.

If the clasts are fragments of a single parent body with a fluid of evolving isotopic composition, the carbonates that precipitated at the early and late stages of alteration may have the largest difference in oxygen isotopic composition. For example, in the case of CM chondrites, which are char-
acterized by a highly variable degree of aqueous alteration (e.g., Browning et al., 1996; Rubin et al., 2007), the $\Delta^{17}O$ and $\delta^{18}O$ of carbonates evolve towards lower values with increasing alteration (Fig. 14, Benedix et al., 2003). No correlation between $\Delta^{17}O$ and $\delta^{18}O$ is observed for carbonates in the Isheyevo clasts of group I (Fig. 14). In addition, the range in $\Delta^{17}O$ exhibited by carbonates in the Isheyevo clasts is almost twice as large as that of the CM carbonates. Thus, the systematics seen in CM chondrites are not observed in Isheyevo clasts. Although the oxygen isotope data are not inconsistent with a hypothesis that the clasts of group I come from a single parent body, they provide no direct support of it.

The lithic clasts with carbonates characterized by $\Delta^{17}O > 0$ could potentially be pieces of the CI or Tagish Lake parent bodies. However, $\delta^{18}O$ of carbonates in Isheyevo and in Tagish Lake do not overlap (Fig. 13). Moreover, as emphasized earlier, (1) the chemical compositions and texture of the dolomite grains in Isheyevo and Orgueil (CI) are different and (2) the chemical compositions of the phyllosilicate-rich matrices are also different from CI chondrites. Thus, oxygen isotopic compositions, mineral chemistry, and petrology of the carbonates do not support a common origin of these clasts and CI or Tagish Lake. Carbonates in Isheyevo with $\Delta^{17}O < 0$ have oxygen isotopic compositions similar to those in Nogoya and Mighei CM chondrites (Benedix et al., 2003). However, the carbonate in CM chondrites is almost exclusively calcite, whereas dolomite and magnesite occur in Isheyevo. Thus, despite comparable oxygen isotopic compositions of the carbonates, the chemical composition of the carbonates argues against a common origin of these lithic clasts in Isheyevo and the CM chondrites.

4.1.4. Parent bodies sampled by the Isheyevo clasts

The group I, II, and III clasts are different from the main chondrite groups and also from the clasts present into different chondrite groups. Hence, they may have sampled parent bodies not represented yet in our collection of meteorites. Moreover, the Isheyevo clasts are different enough in mineralogy and thermal history to suggest that they might have sampled more than one parent body. Indeed, group II clasts are characterized by the presence of chondrules, chondrule fragments and CAIs and are not as hydrated as group I clasts. Group III clasts have experienced some thermal metamorphism, in contrast to groups I and II clasts. Moreover, within group I clasts, variability in term of proportion of the different mineral phases are observed, as well as different oxygen isotopic composition of the carbonates. As already concluded above, this variability may reflect either evolution of oxygen isotopic composition of a fluid on a single parent body, as a result of water-rock interaction, or sampling of different parent bodies with different isotopic compositions of fluids. Although the oxygen isotope data are not inconsistent with the first hypothesis, they provide no direct support of the sampling of a single parent body.

The groups I, II, III clasts in Isheyevo represent three different kinds of materials which experienced secondary alteration in different environments. Among chondrites, objects that differ significantly in mineralogy and mineral chemistry, thermal and aqueous alteration history, and oxygen isotopes are generally assigned to different parent bodies. Accordingly, the Isheyevo clasts may have sampled at least three parent bodies.

4.2. Chondritic lithic clasts in metal-rich chondrites: constraints on their origin and incorporation

Lithic clasts are present in all CH and some CB chondrites (e.g., Krot et al., 2003). Hydrated lithic clasts in the CB chondrites QUE 94411 and HH 237 and in the CH chondrites PAT 91546 and ALH 85085 are mineralogically similar (Greshake et al., 2002). Moreover, as in Isheeyevo, several types of lithic clasts were recognized in the CH chondrite ALH 85083 ( Grossman et al., 1988). All types are fine-grained and opaque in transmitted light. The most common type contains magnesite and dolomite embedded in a fine-grained matrix. The next most-abundant type of clasts, termed reduced clasts, has an equally fine-grained matrix and contains a greater abundance of large olivine crystals. Magnetite is absent and blebs of Fe,Ni-metal are observed instead. Other types of clasts have been observed, some containing calcite instead of dolomite, some with different morphologies of magnetite, some containing osbornite, etc. These characteristics, the distinction between clasts in ALH 85085 based on the presence or absence of metal grains, and the partial resemblance with CI and CM matrices suggest similarities with the lithic clasts present in Isheeyevo. Petrographic diversity of the lithic clasts may not be a peculiarity of the CB/CH-like Isheeyevo chondrite. Every metal-rich chondrite may have in fact sampled common set of parent bodies.

The lithic clasts were incorporated in the final parent body of Isheeyevo after having experienced aqueous alteration in an asteroidal setting. When and how the incorporation happened is yet to be constrained. Two main scenarios can be envisioned: either the lithic clasts were accreted with the high-temperature components, or they were added later by regolith gardening. Timing of the aqueous alteration event could potentially allow to choose between these solutions. For example, $^{53}$Mn–$^{53}$Cr systematics of carbonates in several chondrite classes indicates distinct periods of carbonate formation. The Kaidun breccia apparently contains material that was aqeuosly altered at various times over the first 4 Myr of solar system history (Hutcheon et al., 1999; Petitat et al., 2009). Alteration on the CI parent body started 3–7 Myr after the CAI formation (Hoppe et al., 2007), and continued in CI and CM chondrites for 10–15 Myr ( Endress et al., 1996; Hutcheon and Phinney, 1996; Brearley, 2003). The $^{207}$Pb/$^{208}$Pb ages of chondrules in CB chondrites suggest that they may have been formed at ~5 Myr after CAIs from a vapor–melt plume produced by a giant impact between planetary embryos (Krot et al., 2005). Isheeyevo contains cryptocrystalline chondrule petrographically similar, and having nearly identical oxygen isotopic compositions to those of CB chondrites ( Krot et al., 2007a). Thus, similarly to CB chondrites, the accretion of the high-temperature components of the CB/CH-like Isheeyevo chondrite likely occurred.
around ~5 Myr after CAIs. If the carbonates in Isheyevo formed prior to the impact-induced origin of the CB chondrules, the lithic clasts could have accreted together with the high-temperature components (i.e., Isheyevo is an accretionary breccia). However, if the carbonates in Isheyevo formed later than this event, incorporation of lithic clasts during regolith gardening would be required.

Group II lithic clasts, in particular the ones without magnetite or carbonates and with the largest anhydrous silicates, have experienced a lower degree of aqueous alteration than group I lithic clasts. Group II clasts also experienced a lower degree of thermal metamorphism than group III clasts. Therefore, group II lithic clasts may be the best representative of pristine material. In these clasts, the fragments of olivine and Al-bearing low-Ca or high-Ca pyroxenes (Table 2) are probably pieces of chondrules. Indeed, the Al-rich low-Ca and high-Ca pyroxenes are typical for Al-rich chondrules with skeletal olivine textures in metal-rich carbonaceous chondrites (Krot et al., 2001, 2007b). Moreover, cryptocrystalline chondrules, dominant type of chondrules in metal-rich chondrites, were also observed in the Isheyevo clasts. In particular, a ferrous cryptocrystalline chondrule with a euhedral Fe,Ni-metal grain is present in one of the clast. Such chondrules are found in many CH chondrites and Isheyevo (e.g., Krot et al., 2000; Ivanova et al., 2008) and are absent in other chondrite groups. Thus, at least some of the anhydrous silicates in lithic clasts may be related to the high-temperature component of metal-rich chondrules. The oxygen isotopic compositions of the anhydrous silicates appear to confirm this relationship (Bonal et al., 2009). This would imply that the group II lithic clasts were associated with the high-temperature component of metal-rich chondrites at one point. The group II lithic clasts could be the remains of a body that was nearby the gas-melt plume invoked to explain the origin of chondrules and metal grains in CB chondrites (Campbell et al., 2002; Rubin et al., 2003; Krot et al., 2005), or the body could have been directly involved in the planetary-scale event that triggered the gas-melt plume. This body could be the initial parent body of the CH chondrites (with nebular CAIs and porphyritic chondrules) or a body present in the asteroid belt. The accretion of the surrounding material following the formation of high-temperature components could account for the diversity of the lithic clasts. The low abundance of group II lithic clasts could be explained by a low survival rate of the matrix of the nearby body during the gas-melt event. Hydrogen, carbon and nitrogen isotopic characterization of the group II lithic clasts will bring new constrains on their origin. Large bulk enrichment in heavy nitrogen and numerous 15N-hotspots in some of the clasts of Isheyevo (Bonal et al., 2008b, 2009; Briani et al., 2009) already confirm their uniqueness among our collections of cosmomaterials.

5. CONCLUSIONS

Chondritic lithic clasts are a minor component in the metal-rich chondrites. In Isheyevo, the lithic clasts are petrographically, structurally and isotopically diverse. Their description as a “CI-like” material is too simplistic and wrong. Indeed, the lithic clasts do show some similarities with the matrices of CI, CR and CM carbonaceous chondrites, but none of these is a good match. The lithic clasts in Isheyevo apparently represent samples of at least three parent bodies not represented among known chondrite groups.

Three major groups of lithic clasts were observed in Isheyevo. They are characterized by diverse degrees of aqueous alteration and thermal metamorphism. Group I lithic clasts are the most common in Isheyevo and are characterized by a heavily hydrated mineralogy. With the exception of two clasts they did not experienced thermal metamorphism, as attested by the structural order of the polyaromatic carbonaceous matter. The oxygen isotopic composition of the carbonates is highly variable; this variability is easily explained by the sampling of different parent bodies. Group II lithic clasts are characterized by the presence of anhydrous silicates, microchondrules, and rare microCAIs. The degree of hydration appears to be substantially lower than in the group I. With the exception of two lithic clasts, the polyaromatic carbonaceous matter is highly disordered, attesting to the absence of significant metamorphism. Group III clasts are characterized by the absence of magnetite and the presence of Fe,Ni-metal. The structure of the polyaromatic carbonaceous matter is systematically more ordered than in groups I and II, indicating a degree of thermal metamorphism comparable to 3.00–3.05 carbonaceous chondrites. The mineralogical, isotopic and structural diversity of the lithic clasts can be easily explained by the sampling of several parent bodies, not represented by any known chondrite groups.

Understanding the source(s) of the chondrite lithic clasts and how they were incorporated into the final Isheyevo parent body is required to fully understand the formation history and anomalous characteristics of the metal-rich chondrites.

ACKNOWLEDGMENTS

We thank E. Quirico and S. Duber for providing us with unpublished data. We thank Dr. Mike Weisberg and Dr. Marina Ivanova for critical comments and suggestions on an earlier version of this manuscript. We also thank three anonymous reviewers for their constructive comments, and the associate editor Dr. Hiroko Nagahara. This work was supported by NASA grants NNG05GG49G and NNX08AG58G (G.R. Huss, P.I.), and NNX07AZ43 (A.N. Krot, P.I.). This is Hawai’i Institute of Geophysics and Planetology publication No. 1817 and School of Ocean and Earth Science and Technology publication No. 7876.

REFERENCES


Associate editor: Hiroko Nagahara