Published in final edited form as:

Icarus. 2017 August ; 292: 36–47. doi:10.1016/j.icarus.2017.03.021.

Sedimentary laminations in the Isheyevo (CH/CBb) carbonaceous chondrite formed by gentle impact-plume sweep-up

Laurence A.J. Garvie^{a,b,*}, L. Paul Knauth^b, and Melissa A. Morris^{b,c}

^aCenter for Meteorite Studies, Arizona State University, Tempe, AZ 85287-6004, USA

^bSchool of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-6004, USA

^cState University of New York, Cortland, NY 13045, USA

Abstract

Prominent macroscopic sedimentary laminations, consisting of mm- to cm-thick alternating well-sorted but poorly mixed silicate and metal-rich layers cut by faults and downward penetrating load structures, are prevalent in the Isheyevo (CH/CBb) carbonaceous chondrite. The load structures give the up direction of this sedimentary rock that accumulated from in-falling metal- and silicate-rich grains under near vacuum conditions onto the surface of an accreting planetesimal. The Isheyevo meteorite is the end result of a combination of events and processes that we suggest was initiated by the glancing blow impact of two planetesimals. The smaller impactor was disrupted forming an impact plume downrange of the impact. The components within the plume were aerodynamically size sorted by the nebular gas and swept up by the impacted planetesimal before turbulent mixing within the plume could blur the effects of the sorting. This plume would have contained a range of materials including elementally zoned Fe-Ni metal grains that condensed in the plume to disrupted unaltered material from the crust of the impactor, such as the hydrated matrix lumps. The juxtaposition of hydrated matrix lumps, some of which have not been heated above 150 °C, together with components that formed above 1000 °C, is compelling evidence that they were swept up together. Sweep-up would have occurred as the rotating impactor moved through the plume producing layers of material: the Isheyevo sample thus represents material accumulated while that part of the rotating planetesimal moved into the plume. Vibrations from subsequent impacts helped to form the load structures and induced weak grading within the layers via kinetic sieving. Following sweep-up, the particles were compacted under low static temperatures as evidenced by the preservation of elementally zoned Fe-Ni metal grains with preserved martensite α_2 cores, distinct metal-metal grain boundaries, and metal-deformation microstructures. This meteorite provides evidence of gentle layer-by-layer accretion in the early Solar System, and also extends the terrestrial sedimentary source-to-sink paradigm to a near vacuum environment where neither fluvial nor aeolian processes operate.

*Corresponding author at: Center for Meteorite Studies, Arizona State University, Tempe, AZ 85287-6004, USA, lgarvie@asu.edu (L.A.J. Garvie).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.icarus.2017.03.021.

1. Introduction

Planetary formation is thought to be a largely energetic process dominated by collisions between materials produced by condensation in the early Solar nebula, with gravity as the binding force (Weidenschilling and Cuzzi, 2006). Many asteroids attest to this early energetic history through their rubble-pile structure composed of gravitationally bound aggregates of impact debris (Richardson et al., 2002). Brecciation and the effects of shock metamorphism in meteorites are common signs of an energetic past and attest to the importance of impact processing (Sharp et al., 2006; Zolensky and Ivanov, 2003). While brecciation is a common feature of primitive meteorites, none have so far been described that show macroscopic structures suggesting sedimentation.

However, small inclusions within some carbonaceous chondrites show features akin to sedimentary structures. For example, a mm-sized dark inclusion within the Vigarano CV3 chondrite shows arcuate bands that may have formed through dust accumulation on a parent-body surface (Johnson et al., 1990; Kojima and Tomeoka, 1997). Also, a dark inclusion in the Gujba (CBa) chondrite shows “flame structures” that are interpreted as having formed either through uniaxial deformation or through seismic shaking of a previously layered material (Nehru et al., 2014). Layer-like structures in meteorites have rarely been observed, among them some formed by alteration (Tomeoka and Buseck, 1985) and plastic deformation or oriented mineral growth (Akos et al., 2014), but none of these layers is sedimentary in origin. Note, the “sedimentary” term is used in this paper in a different context than in Earth sciences. Instead of deposition from a fluid, solid material settles and accumulates forming rock, although without atmosphere and under low gravity. Despite these limited examples, evidence of accretion on a parent body is rarely preserved, though many carbonaceous chondrites show evidence of accretionary processes in the solar nebula, e.g., Metzler et al. (1992).

Recently, a new primitive meteorite named Isheyevo has been discovered (Ivanova et al., 2008) that shows fine laminations akin to sedimentary layers (Chaumard et al., 2014; Morris et al., 2012; Morris et al., 2015). This meteorite is classified as a CH/CBb chondrite (Ivanova et al., 2006; Ivanova et al., 2008). The metal-rich carbonaceous chondrites (comprising the CH – ALH85085-like and CB – Bencubbin-like groups) show unusual features not seen in other chondrites, including lack of interchondrule fine-grained matrix, large variations in the metal grain to silicate ratio (Campbell et al., 2005; Goldstein et al., 2007; Ivanova et al., 2008; Rubin et al., 2003; Weisberg et al., 2001), and the highest whole-rock ^{15}N enrichments yet recorded (Bonal et al., 2010b). Chondrules within the CB meteorites Gujba and Hammadah al Hamra (HaH) 237 have an age of 4562 Myr (Krot et al., 2005), which is ~5.5 Myr after the formation of the first radiometrically dated materials in meteorites called calcium-aluminum-rich inclusions (CAIs) of 4568.2 Myr (Bouvier and Wadhwa, 2010) and 4567.3 Myr (Connelly et al., 2016). However, the CB parent body also underwent a later major impact at ~4200 Myr (Marty et al., 2010); evidence for this impact is a suite of high-pressure minerals (Garvie et al., 2011; Garvie et al., 2014; Weisberg and Kimura, 2010). Thus, it is possible that the younger ages for the CB chondrules relative to CAIs represent a reset age (Weisberg and Kimura, 2010). While shock-formed materials are described from the CB meteorites, e.g., Garvie et al. (2011,2014), Weisberg and Kimura

(2010) and Weisberg et al. (2006), none have so far been reported from Isheyevo. By 5 Myr post CAIs, our protoplanetary disk had entered the transition disk phase and the modeling of Isheyevo's formation provides constraints on the evolution of our Solar nebula (Morris et al., 2015).

Isheyevo is composed of a well-sorted mixture of metal grains, chondrules, CAIs, and fine-grained lithic clasts, some of which have experienced extensive aqueous alteration (Bonal et al., 2010a; Ivanova et al., 2008; Krot et al., 2007). Particularly striking in Isheyevo are hydrated and anhydrous fine-grained lithic clasts (Ivanova et al., 2008,2009), some with extreme ^{15}N enrichments ($\delta^{15}\text{N}$ to $+4900 \pm 300\text{‰}$) (Bonal et al., 2010b; Briani et al., 2009). Some clasts contain phyllosilicates and poorly ordered organic matter (Bonal et al., 2010a,b; Briani et al., 2009; Ivanova et al., 2009). Raman spectra of the organic matter are consistent in shape with those from unmetamorphosed carbonaceous chondrites, such as Orgueil (CI), Renazzo (CR2), and Murchison (CM2) (Bonal et al., 2010a; Briani et al., 2009). These spectral similarities between organic components imply that at least some of the Isheyevo lithic clasts, and hence the region of the parent body preserved as the Isheyevo meteorite, escaped heating above $\sim 150^\circ\text{C}$. While detailed isotopic and compositional studies have been undertaken on individual components (Ivanova et al., 2008; Krot et al., 2007,2012), description of the sedimentary features and formation scenario of this unusual meteorite has so far received little attention (Chaumard et al., 2014; Morris et al., 2012,2015).

Some of the Fe-Ni metal grains in Isheyevo show smooth Fe, Ni, Cr, and Co zoning patterns, with higher Ni and Co in the grain cores relative to the rims and opposite zoning for Fe and Cr (Ivanova et al., 2008). Similar elementally zoned Fe-Ni grains have been identified in CH and CBb chondrites (Campbell and Humayun, 2004; Campbell et al., 2001,2005; Goldstein et al., 2007; Ivanova and Petaev, 2015; Meibom et al., 1999; Weisberg et al., 1988), whereas they are absent in the CBa chondrites, such as Bencubbin and Gujba (Rubin et al., 2003). Microstructural characterization of these metal grains in the CH chondrites is consistent with growth and cooling to temperatures below 500 K on time scales of a few days (Goldstein et al., 2007). A number of models have been invoked to explain the formation of these metal grains, including creation in the solar nebula e.g., Newsom and Drake (1979) and Petaev et al. (2001), or in an impact plume formed from colliding planetesimals e.g., Wasson and Kallemeyn (1990). The geochemical characteristics of the zoned metals grains are more consistent with their formation in an impact plume rather than in the solar nebula (Fedkin et al., 2015; Krot et al., 2005; Rubin et al., 2003).

Any model proposed to explain the sedimentary layering in Isheyevo needs to account for its primary features; viz., well-sorted grains, juxtaposition of high-temperature materials with those that escaped heating above $\sim 150^\circ\text{C}$, sedimentary layering, and evidence for gentle accretion. Here we interpret the observed sedimentary and petrographic features in light of a sweep-up model from a size-sorted plume onto the Isheyevo planetesimal. Consistent with current thinking, this plume could have formed from the collision of planetary embryos (Fedkin et al., 2015; Krot et al., 2005; Rubin et al., 2003). This sedimentary accretion scenario is based upon modeling of the glancing-blow impact of early planetesimals (Asphaug et al., 2011), and modeling of the dynamics of the resulting impact plume

followed by gentle sweep-up of the plume products back onto the impacted body (Morris et al., 2012,2015). Fedkin et al. (2015) concluded that impacting planetesimals of CR chondritic compositions could produce the necessary chemical conditions for condensation of the CB metal grains and chondrules.

Here we describe the sedimentary features in Isheyev. This meteorite is our first extraterrestrial sample with macroscopic features that records quiescent accretion onto an early parent body during the period of planetary formation, approximately 0.5 Ga before the oldest known Earth rocks.

2. Materials and methods

2.1. Samples

Isheyev was found in 2003 near the village of Isheyev in Bashkortostan, Russia. It was a loaf-shaped, 16-kg meteorite covered in dark brown, partially weathered fusion crust (Ivanova et al., 2005) – see www.lpi.usra.edu/meteor/metbull.php?code=30726. Most pieces available for study are cm-sized. They show segregation of metal-rich and metal-poor materials (Ivanova et al., 2008; Krot et al., 2007), although the larger scale associations between the lithologies has been only briefly described (Chaumard et al., 2014). In addition to these small pieces, six almost complete cross-section slices were cut, two of which were acquired by the Center for Meteorite Studies, Arizona State University (ASU#1580_1, 234.1 g, 15 × 18 × 0.2 cm; and ASU#1580_10, 421.0 g, 15 × 15 × 0.4 cm) (Figs. 1, S1 and S2), together with an end cut (ASU#1580_11, 249.3 g, 12 × 7 × 1 cm, Fig. S3). The slices and end cut were polished to 1 μm with diamond polish then with 0.2-μm cerium oxide. Eight one-inch-round sections (ASU#1580_B_1 to 1580_B_8) were polished and the metal microstructures studied after etching with nital (2% HNO₃ in 98% methanol) and after chemical tint etching. In addition, one ultrathin thin section was studied (ASU#1580_A_1). The round sections were made from small pieces acquired separately from the large slices. It is unknown where these small pieces fit into the stratigraphic sequence of the large slices. However, all of the large slices have a section cut from one end, so it is possible that the small pieces are from the cut-off end.

2.2 Metallographic tint etching

Elemental examination of metal particles is normally the domain of scanning electron microscopy (SEM) and electron probe micro-analysis (EPMA), allowing detailed single-particle investigation e.g., Goldstein et al. (2007), and broader information through elemental mapping. However, this type of mapping is time consuming. Detailed metallographic information can also be revealed after etching, primarily with nital, which has been the cornerstone of meteoritic iron structural analysis e.g., Buchwald (1975) and Goldstein et al. (2007), and coupled with elemental concentrations determined through EPMA and instrumental neutron-activation analysis (INAA) forms the basis of iron meteorite classification (Goldstein et al., 2009). Nital differentially etches the meteoritic metal phases producing a surface topography that provides structural information on the metal and associated phases, such as phosphides, carbides, and sulfides. The structural information gained through optical and SEM examination of these polished and etched

surfaces is revealed through the light-shade contrast between the different phases, producing “black-and-white” images. It is also possible to tint etch metals, with the tint color providing structural and compositional information (Beraha and Shpigler, 1977). Tint etching is used extensively in the metallurgical fields, but only rarely on iron meteorites (Zucolotto and Klein, 2001; Zucolotto and Pinto, 2001).

Two tint etches were used - sodium bisulfite (NaHSO_3), and potassium metabisulfite ($\text{K}_2\text{S}_2\text{O}_5$). These tints were chosen as they reveal elemental zoning and deformation microstructures in Fe-Ni alloys and ferritic steels (Beraha and Shpigler, 1977; Guellard, 1956; Vilella and Kindle, 1959). The potassium metabisulfite tint-etch produces color variations on the metal grains that are quantifiably related to Ni content. While the sodium bisulfite tint-etch also produces colors related to Ni content, it also reveals relative crystallographic orientations and deformation microstructures (Guellard, 1956).

Prior to tint etching, samples were polished with 1- μm diamond polish and then 0.3- μm alumina. The polished samples were then washed and immersed into freshly prepared tint-etch solution, removed and washed in water then methanol and dried under warm blowing air. Tint-etch solutions used and tint times are as follows: 20 g sodium bisulfite in 100 ml water and sample immersed for ~10 s; and, 3 g potassium metabisulfite in 100 ml water and tint etched for ~30 s. Care was taken to not touch the surface of the tint-etched samples as the tint layer is easily scratched. The polished, nital etched, and tint-etched samples were viewed with a petrographic microscope (Leica DM 2500P) with reflected light under bright-field, polarized, and Nomarski imaging.

2.3. Scanning electron microscopy and microprobe analysis

Following optical examination of the tint-etched samples, the sections were repolished with 1- μm diamond and 0.3- μm alumina, coated with carbon and analyzed by SEM and EMPA with wavelength dispersive spectroscopy (WDS) at The Michael J. Drake Electron Microprobe Laboratory (University of Arizona) using the Cameca SX100 Ultra electron probe. Element line scans were acquired across selected grains so as to correlate the tint-etch colors with elemental data. Analyses were performed at 15 kV accelerating voltage, 40 nA beam current and 20 s counting time. Selected element maps were acquired at 15 kV accelerating voltage and a current of 200 nA. Elements analyzed were Fe, Ni, Si, P, S, Cr, and Co for which totals for the metals were typically between 99.5 and 100.5 wt%.

2.4. Grain measurements

Measurements of metal grain diameter, orientation, and aspect ratio were performed in Photoshop on photographs of six areas from the large section #1580_10 (Fig. 1) using a method similar to that described in Meibom et al. (2005). Reflected-light photographs were taken from 4.5- × 3-mm-sized areas, with the long axis of the photos parallel to the laminations so that potential relationships between orientation and aspect ratio could be related to orientation of the sedimentary features. Orientations were determined by drawing a line (using the Ruler Tool in Photoshop) along the major axis of the grain: the orientation and length of the line were then recorded. The length of the minor axis was then measured.

The extent of particle flattening is expressed as the aspect ratio of major axis/minor axis. For reasons described below, similar measurements were not made for the silicate grains.

3. Results

3.1. Sedimentary structures

The slices and end cut exhibit features dominated by metal that are traversed by a series of roughly parallel layers delineated by the nonmetallic components. Visually, the polished slices are dominated by metal that is peppered with fine silicates, mainly in the 50- to 300- μm size range, with rare grains to 16 mm. The silicates outline features resembling sedimentary structures including laminations, faulting, and load structures (Figs. 1, 2 and S1–S4). These features are visible in both ASU slices, and in three other privately owned slices. The continuity of the stratigraphic features through the available slices and end cut is consistent with them traversing the whole meteorite; importantly, the meteorite was fortuitously cut perpendicular to the layers.

Optical analysis of the polished slices reveal ~62 areal% Fe-Ni metal, however this value varies among the stratigraphic units and on the scale of the measurements. At the mm-scale, the metal areal percentages range from 10 to 85%. The boundaries between the metal- and silicate-rich lithologies range from abrupt (~ 1 mm) to gradational (~ 1 cm): it is these metal-silicate variations that we define as stratigraphic units and structural features (Units A–G, Fig. 2, larger image available in the supplementary data Fig. S4). These units form roughly planar laminated beds that are bounded by a fault at the bottom left of the slice and a shear zone at the top right (Figs. 2, S4). The individual units range from 1.5 cm (Unit C) to ~5 cm (Unit F) in thickness, though each of the units show additional structures and fine laminations.

Unit A is metal rich containing weakly developed parallel laminae: the boundary with Unit B is irregular but readily visible as B is richer in silicate grains. The laminae are delineated by variations in the metal to silicate ratio. B is weakly laminated with well-sorted silicates and metal containing few grains larger than 100 μm . The top of C is delineated by a thin metal-rich horizon ~ 1-mm thick. C shows several alternating metal-rich and thin silicate-rich laminae. Unit D is metal-rich compared to C and B and shows lobe-like structures through the lower half. The lobe-like features are visible as abrupt (over 1–2 mm) changes in the metal/silicate ratio. The base of Unit D is defined by lobe-like structures that protrude into E. The top of E is traversed by a layer of coarse silicates and metal grains, many of which are in the 500–1000- μm size range, and the base is metal rich and lacks the coarse silicates. Unit F exhibits several silicate-rich layers and has an iron-rich base with well-developed finger-like lobes that protrude into the silicate-rich Unit G.

The small fault-like offsets disrupt the planarity of the well-defined laminations and can be traced perpendicular to the layering through stratigraphic Units B, C, and into D. Upward dampening of the deformation left low-density Unit B relatively undeformed. In this interpretation, the thick arrow shows stratigraphic up (Fig. 2) determined from the downward bulge of the load structures, and thus Unit A is stratigraphically the youngest. The fault at the lower left of slice #1580_1 (Fig. 2) has a 2.3 cm offset, which is most readily

visible by the displacement of coarse silicate layer in Unit E. The fault plane is roughly perpendicular to the bedding on either side. The coarse silicate layer is smeared along the fault zone; this smearing is similar to soft-sediment faults and indicates that the deformation occurred while the sediment was unconsolidated. The sheared zone to the top right of the slice (double sets of arrows in Fig. 2) separates an intact region of displaced sediment (Units C–F) by 6 cm and rotated 7° relative to the main part of the slice. The shear zone shows clearly recognizable coarse silicates from Unit E and fine-grained Unit B.

Visual comparison between the two complete slices (Figs. S1 and S2) reveal structural and sediment variations within the same units but perpendicular to the cut surfaces. For example, the Unit C laminae in slice #1580_1 are more clearly developed compared with the same area in slice #1580_10. Also, the left side of Unit C in #1580_10 shows a region dominated by silicates that is 2 cm long and 0.5 cm thick, that is absent in slice #1580_1. Similar differences are visible when comparing the same areas for the coarse silicate layer in Unit E and the slump structures at the base of Unit F.

3.2. Optical and SEM microscopic examination

Optical microscopic examination of the polished sections, prior to tint etching, shows highly reflective interlocking, irregularly shaped metal and non-metal grains and circular chondrules (Fig. 3). Little structure is visible from the polished metal except for inclusions such as silicates and troilite. Troilite grains are rare. The fine-grained lithic fragments are of similar size as the chondrules and silicate fragments, and do not show evidence of having been fragmented or deformed during sweep-up or after sedimentation. There is no visible porosity. The metal grains have well-defined irregular to curved grain boundaries.

3.2.1. Metal grain composition and structure—A combination of optical metallographic and SEM/EPMA observations reveal a range of metal grain types, similar to those previously described in the CH chondrites and Isheyevo (Goldstein et al., 2007; Ivanova and Kononkova, 2009; Ivanova et al., 2008). Isheyevo metal grains are dominated by those that are (1) elementally zoned with Ni-rich, Fe-poor interiors, (2) unzoned single-crystal kamacite, (3) cellular polycrystalline kamacite, (4) decomposed into resolvable kamacite and Ni-rich metal, (5) unzoned Ni-rich, (6) unzoned Ni-rich with inclusions, (7) kamacite with inclusions, and (8) elementally zoned with Ni-rich cores, but with cores separated into Ni-rich and Ni-poor phases. Examples of grain types 1 through 7 are shown in Fig. S5. In addition, a range of rare metal particles, not fitting into the above categories were also found, including Si-rich (~6–12 at%) kamacite, Co-rich kamacite, inversely zoned with Fe-rich, Ni-poor cores and Ni-rich, Fe-poor rims, a spherical grain of complexly intergrown Fe-P-Si, and kamacite with silicate rods.

Potassium metabisulfite tint-etched sections show vivid colors on the Fe-rich metal grains that correlate with Ni content (Figs. 4, 5, S5). Grains with uniform compositions show consistent tint colors (e.g., grain D in Fig. 4), whereas those whose Ni content varies show color gradations (grains A and B, Fig. 4). Correlation between tint color and Ni-content was undertaken on the same grains that were first tint etched and photographed, then repolished and analyzed by EMPA (Figs. 4, 5). Under the tinting conditions described above (Materials

and Methods), the colors correlate with Ni content as, yellowish (~ 3–4 at% Ni), pale blue (~4–5 at% Ni), dark blue to purple (~6 at% Ni), brownish tan (~7 at% Ni), light tan (~8 at% Ni). Above approximately 10 at% Ni, the metal is only lightly stained and higher Ni content metal, e.g., > 20 at% Ni, is unstained and highly reflective. Inclusions such as phosphides, sulfides, and silicates remain unstained. Particles with complex microstructures composed of differing compositions are revealed through tint etching. For example, a grain decomposed into Ni-rich and Ni-poor subgrains shows light or unstained Ni-rich lamellae in a stained Ni-poorer groundmass (grain C, Fig. 4).

Particularly striking on the potassium metabisulfite tint-etched samples are the Fe-Ni zoned grains with Ni-rich cores. EMPA shows continuous compositional gradients at the micron level, which is further corroborated by the smooth color gradations (Fig. 4 grains A and B; Fig. 5). No Ni-poor or -rich precipitates were identified by EMPA, BSE imaging, or through tint etching in these zoned particles. Most tint-etched zoned metals show a largely featureless low-Ni kamacite rim and central high-Ni region of martensite α_2 . Nital etching reveals a submicron lath-like morphology of the martensite α_2 core (Fig. 5C, D), consistent with the lath martensite observed by transmission electron microscopy of elementally zoned metal in CH chondrites (Goldstein et al., 2007).

In addition to highlighting Ni zoning and complex microstructures, sodium bisulfite tint etching more clearly reveals deformation microstructures and crystallographic orientations (Fig. 6) than potassium metabisulfite. Many grains show well-developed curvilinear features consistent with families of slip lines (also called shear bands), or of deformed Neumann bands (Fig. 6). The microscopic observations reveal the heterogeneous nature of the plastic deformation both within and between the metal grains. For example, some elementally zoned metal grains are plastically deformed and retain the Ni zoning, but also show extensive shear bands and deformed Neumann bands in the kamacite rim (Fig. 6A). The Ni-rich cores can also show shear bands and formation of distinct martensitic grains with irregular boundaries (Fig. S5, grains 1c). The mechanical deformation features reveal the higher stresses and deformation in the rims of the grains compared with the interiors, with the highly deformed edges showing a dark etch relative to the relatively undeformed centers of the grains (Fig. 6C,D). Some grains show curvature of the shear and Neumann bands, which is indicative of low-temperature plastic deformation (Samuels, 1999). Some of the larger ferrite grains show Neumann bands, which can form via shock, but also through extensive plastic deformation (Samuels, 1999). In other grains, Neumann bands and shear bands occur within the same deformed grain, indicative of a combination of shock and plastic deformation (Fig. 6D). The deformation seen in the metals may be akin to low temperature creep plasticity, which has been observed in steels, e.g., Kassner and Smith (2014).

3.2.2. Metal grain shapes—The degree of flattening of metal grains across the large slice (#1580_10) was determined by measuring the angle between the longest axes of grains relative to a reference angle from four areas showing parallel layering. These angles were measured with the 0° (also 180°) parallel to the layering. The metal grains from areas 1, 2, and 3 (Fig. 1) show a preferential orientation parallel to the layering, although this flattening is relatively small (Fig. 7). Such deformation is consistent with a compressive load

perpendicular to the layering. Aspect ratio measurements were not made on the silicates, since they did not deform similarly to the metals, as evidenced by the strong deformation of metals around silicates in the shear zones, without evidence for silicate plasticity or brittle deformation. Thus, the silicates are acting akin to undeformed porphyroclasts that are harder than the surrounding matrix in deformed rocks, e.g., White et al. (1980). The metals also showed “spikes” in the orientation data at high angles, which is the result of deformation of the metals grains around the undeformed silicates. Area 4 shows parallel layers though the metal grain long axes are peaked at 40°–50° relative to the layering (Fig. 7). Metal angles and deformation was also measured in Areas 5 and 6 within the shear zone (Figs. 1 and 2). Here the angles were measured relative to the layering in the adjacent Area 4 (in Unit C). The metal grains show minor flattening with a spread peaked between 40° and 70°: this data overlaps that seen in the adjacent Area 4 (Fig. 7).

The mild degree of deformation is also reflected in the aspect-ratio mode, which is around 1.5 for all areas analyzed (Fig. 8). The few grains with large aspect ratio values have been deformed around silicate grains. Isheyevo shows a lower degree of mechanical deformation than measured in the CB chondrites QUE 94411, HaH 237, and Bencubbin (Meibom et al., 2005), where > 85% of the particles have their longest axis oriented < 45° from the reference axis, versus 69% for Isheyevo. In addition, the grains in these meteorites are on average more deformed than in Isheyevo, with the mode in their axis ratio of 1.8–2.

3.2.3. Metal-metal grain boundaries and fine-grained material—Imaging of the polished sections, particularly after nital etching, shows prominent metal-metal grain boundaries, with the boundaries containing a combination of glass, fine-grained material, silicate fragments, and rare shock melt. High magnification optical and SEM images show that these boundaries are commonly filled by thin nonmetallic veins and silicate fragments (Fig. 9). Petrographic optical examination of an ultrathin thin section shows that these veins are typically < 3 μm thick, commonly yellow-orange in plane-polarized light, and isotropic when viewed between crossed polarizers suggesting that they are glass. The veins between the metal grains are of variable thickness and can locally be recognized between the silicate-metal grains. Backscattered electron images of these veins are brighter than the typical Fe-poor chondrules but darker than the adjacent metals grains. WDX analysis of these grain-boundary films was complicated by their narrow width relative to the interaction volume of the electron beam and the fact that they are embedded in the high Z metal. However, WDX show them to be ferrous silicate material with totals of between 82 and 87%, and varying compositions (in wt%, $n = 4$ from four separate veins) SiO_2 , 22.6 ± 6.5 ; MgO , 5.8 ± 5 ; FeO , 49.5 ± 8.2 ; CaO , 0.5 ± 0.4 ; Al_2O_3 , 0.5 ± 0.3 ; Cr_2O_3 , 0.2 ± 0.1 ; P_2O_5 , 0.1 ± 0.03 ; SO_2 , 0.6 ± 0.4 ; K_2O , 0.4 ± 0.2 ; and, Na_2O , 0.8 ± 0.3 . Recognizable fine-grained material is rare but locally present as sub-micron-sized opaques and most readily visible around chondrules (Fig. 10A). Similar fine-grained material surrounding chondrules was previously recognized in Isheyevo (Ivanova et al., 2008).

3.2.4. Shear zones and shocked material—Two shear zones occur in the Isheyevo sections and in one of the polished sections (ASU#1580_B_1). They are characterized by a < 200 μm thick plane of intensely deformed metal, with grains that appear to flow around

silicates. Shock-melt is sparse and heterogeneously distributed as small (to 100 μm), patches between metal grains and metal-silicates. For example, it occurs in sections #1580_B_1, _4 and _5, but absent in section _3. The visibility of the shock melt is greatly accentuated by the tint etching, as the melt material does not color and so remains reflective and easy to identify. The melt commonly occurs as amoeboid regions of Fe/Ni-metal/sulfide with embedded spheres of silicates (Fig. 10B), and less commonly as droplets of Fe/Ni-metal/sulfide embedded in silicate glass.

4. Sedimentary environment

The coarse-grained CBa bencubbinites (e.g., Bencubbin-Weatherford-Gujba) have been suggested to represent a depositional component from an impact-generated vapor plume, whereas the CBb chondrites HaH 237 and QUE 94,411 were similarly generated but in a different portion of the same plume (Rubin et al., 2003). Krot et al. (2005) suggested that the CB chondrites formed from an impact-generated, gas-melt plume produced by two impacting planetary embryos. This mechanism was then quantitatively modeled as a glancing blow between two molten planetesimals, with the production of a fan of ejecta downrange of the impact (Asphaug et al., 2011). This model is the only 3D model to date of planetesimal impacts that predicts droplet production consistent with chondrule formation, in which the ejecta is predicted to contain primitive, undifferentiated material originating from a thin crust of the impactor. Modeling shows that the ejecta is dominated by material from the impactor, including material from the unmelted crust and molten material from its interior, set within a vapor plume (Asphaug et al., 2011). Numerical modeling shows that materials from the impact plume can be swept up by the impacted body moving through the plume, whereas an alternative reaccretion scenario via gravitational settling is physically implausible (Morris et al., 2015).

Numerical modeling shows that size sorting of the grains could occur within the plume as it expands and before the grains are stopped by the nebular gas (Morris et al., 2015). Initially, the plume would remain intact and move as a single unit during which time individual components, such as the zoned metal grains, would condense. The components in the ejecta fan will travel varying distances before stopping relative to the impacted body depending on the particle's density and radius, thus sorting the grains according to size and composition. As a consequence of this sorting, for any distance in the plume relative to the impacted body, the silicates will be proportionately larger than the metal grains. Such a size difference is indeed measured. For example, a typical area of Isheyevo shows metals with an average radius of 33 μm ($n = 161$) and silicates and fine-grained lithic clasts with radius of 60 μm ($n = 56$). The rotating survivor of the impact gently swept up the size-sorted materials as it moved through the ejecta plume (Morris et al., 2015).

Several pieces of evidence are consistent with gentle sweep-up. Modeling of the sweep-up (Morris et al., 2015) suggests impact speeds of grains in the plume onto the impactor body on the order of 25–500 m/s. Sweep-up likely occurred at the lower-end of the predicted velocities in order to preserve the fine-grained lithic fragments upon impact with the Isheyevo parent-body surface. This velocity constraint is further dictated by the occurrence of the fragile phyllosilicate-rich fragments (Bonal et al., 2010a). A qualitative estimate of the

maximum impact velocity is provided by the compression strength of the clay fragments using the relationship $P \approx rV^2$ (Popova et al., 2011; Weidenschilling and Cuzzi, 2006), where P is the fragmentation strength, r density, and V velocity. The tensile strength from the few measured carbonaceous chondrites range from 0.3 to 30 MPa (Cotto-Figueroa et al., 2016; Tsuchiyama et al., 2009), which is within the range for unfired clay bricks (Oti et al., 2009). Using the above relationship, this strength range corresponds to velocities of ~30–~200 m/s, which is within that predicted by the modeling (Morris et al., 2015). Significantly higher sweep-up velocities, i.e., >400 m/s, would have resulted in fragmentation of silicates, devolatilization of the clays, and splat welding of the metal grains upon impact (Assadi et al., 2003; Tyburczy et al., 1986). For example, cold spraying of TiO_2 (a brittle ceramic) particles onto metal surfaces at high velocities, >590 m/s, resulted in fracturing and breakup of the individual TiO_2 particles upon impact and plastic deformation and shearing of the metal substrate (Kliemann et al., 2011). At similar velocities, stainless steel particles deformed and stuck upon impact with metal forming lenticular and parachute-shaped grains (Borchers et al., 2008). The silicate and metal grains in Isheyevo do not exhibit the deformation microstructures indicative of high impact velocities.

The low-velocity sweep-up of the plume material onto the rotating planetesimal produced dry, weakly cohesive sediment, with thicknesses of several meters (Morris et al., 2015). Accretion recorded by the Isheyevo mass would only have occurred while that part of the rotating planetesimal moved into the plume. As such, the Isheyevo layers do not represent a continuous and uninterrupted accretion sequence; instead the layers record snap shots in time through the plume. Thus, some of the metal-silicate variations seen in the Isheyevo strata may reflect heterogeneities in the impact plume, which were further modified by post-depositional effects. However, it is difficult to explain the rhythmic metal-silicate variations prominent in Units B and C as resulting solely from such variations in the plume. Instead, the separation of metal and silicates giving rise to the visible layers were likely accentuated by post sweep-up kinetic sieving. Dry granular materials exhibit a range of counterintuitive phenomena that likely account for some of the Isheyevo features. Size and density separation of particles through shaking (the “Brazil nut effect” also called kinetic sieving) (Kudrolli, 2004), likely accounted for separation of similarly sized silicates and metal within individual layers after deposition. Vibration of the planetesimal, which is probably necessary to initiate grain movement and segregation, could occur through impacts subsequent to sweep-up from the plume.

The downward protruding lobe-like features at the bases of Units F, E, and D are interpreted as load structures akin to those in terrestrial aqueous deposits, where dense sediment is deposited over, and protrudes into, a less dense layer (Allen, 1984). The large density difference between the metal-rich Unit F (Ni-rich Fe with $\rho \sim 8 \text{ g/cm}^3$) above the silicate-rich Unit G resulted in post-depositional penetration of the denser material into the less dense layer. This downward penetration caused deformation in overlying Units E and D. Unlike terrestrial load structures facilitated by sediment being wet and oozy, the Isheyevo structures formed under near vacuum and were probably facilitated by vibrations from impacts. The less-dense Unit C maintained a relatively uniform contact with D but slumped downward along small fault-like offsets (dashed lines).

The faults traversing Units B and C show distinct necking and attenuation of the layers (Fig. 2), suggesting that the sediment was weakly cohesive and behaved macroscopically like soft sediment during deformation. The sheared zone to the top right of slice #1580_10 (double sets of arrows in Fig. 2) separates an intact region of displaced sediment (Units C to F) by 6 cm and rotated 7° relative to the main part of the slice. The shear zone shows clearly recognizable coarse silicates from Unit E and fine-grained material from Unit B. The coarse-silicate layer is smeared along the fault zone; this smearing is similar to soft-sediment faults and indicates that the deformation occurred while the sediment was unconsolidated. Further evidence that this faulting took place before consolidation is illustrated by the metal grain shapes, which have similar flattening values and aspect ratios as the grains within the adjacent layered sediment (Fig. 8).

Following sweep-up and formation of the macroscopic sedimentary structures described above, the Isheyev mass was compacted under low static temperatures. Evidence for the low temperatures is provided, in part, by the occurrence of the zoned Fe-Ni metal grains with martensitic α_2 cores. Modeling and thermodynamic constraints demand that these zoned metals formed by condensation from a gas on the time scale of several days, with subsequent fast cooling within a few hours or days (Goldstein et al., 2007). This fast cooling ensures the preservation of the martensitic α_2 cores. Slower cooling would produce a Widmanstätten pattern by the mechanism $\gamma \rightarrow \alpha_2 + \gamma \rightarrow \alpha + \gamma$ (Yang and Goldstein, 2006). Similarly, the zoned-metal structure is sensitive to secondary heating, and their presence shows that they were not heated above ~230 °C, otherwise the martensite α_2 would exsolve Ni-rich taenite and α kamacite (Goldstein et al., 2007). Similar time scales are also suggested by the reaccretion modeling, which predicts that the rotating impacted body swept up material downrange of the collision only a few days after the impact (Morris et al., 2015). Further, the preservation of the individual metal particle grain boundaries is consistent with low-temperature plastic deformation. Such deformation can occur at room temperature, e.g., Kassner and Smith (2014) and Liu et al. (2001).

Even lower maximum temperatures are demanded at the sweep-up site by the preservation of the poorly ordered polyaromatic carbonaceous matter in some of the fine-grained lithic clasts in Isheyev Bonal et al., 2010a; Briani et al., 2009. For example, Raman spectra from one clast reveals organic matter with a low degree of thermal metamorphism, similar to that found in Murchison and Cold Bokkeveld (CM2) carbonaceous chondrites. Oxygen isotopic measurements of Ca-carbonates in these two CM2 chondrites suggest maximum alteration temperatures of ~150 °C (Verdier-Paoletti et al., 2017). Bonal et al. (2010b) show that close to 80% of the lithic clasts have Raman spectral shapes consistent with poorly ordered organic materials, similar to that in Orgueil (CI) and Renazzo (CR2). These observations are consistent with the Isheyev sample as a whole reaching bulk temperatures not exceeding 150 °C, though it may have been significantly lower.

It is unlikely that the pressure needed for compaction occurred at the surface of the accreting body, as post impact accretion would only produce meter thicknesses of sediment (Morris et al., 2015). Subsequent impacts near where the preserved Isheyev meteorite originates, would likely have obliterated the sedimentary features. However, it is possible that the Isheyev sample accreted in a topographic low on the parent body, such as an impact crater.

Thus, further impacts would have further buried the Isheyevo material to depths where later impacts caused post sedimentary compaction and shock features, though it is difficult to disentangle shock features that may have occurred on the Isheyevo parent-body, from those that occurred during its breakup.

The local pockets of glassy ferrous silicate containing droplets of Fe-Ni sulfide are similar to those found between metal grains in the CB carbonaceous chondrites QUE 94,411, HaH 237 and Bencubbin (Meibom et al., 2005). This material is interpreted as “remains of the missing matrix”, that was subsequently shocked (Meibom et al., 2005). Similarly to Isheyevo, these CB chondrites also contain elementally zoned Fe-Ni grains in contact with the shock melts, indicating that the shock did not significantly increase the bulk rock temperature. However, unlike the CB chondrites studied by Meibom et al. (2005), Isheyevo also contains unshocked fine-grained material (Fig. 10A), which was also observed as fine-grained, phyllosilicate mantles around chondrules (Ivanova et al., 2008). The heterogeneous distribution of the shocked interstitial matrix is consistent with the localized nature of shock products in meteorites (Sharp et al., 2006).

5. Conclusions

The Isheyevo meteorite is the end result of a combination of events and processes that we suggest was initiated by the glancing blow impact of two planetesimals. The smaller impactor was disrupted forming an impact plume downrange of the impact. The components within the plume were aerodynamically size-sorted by the nebular gas and swept up by the impacted planetesimal before turbulent mixing could blur the effects of the sorting (Morris et al., 2012,2015). This plume would have contained a range of materials including the zoned Fe-Ni metal grains that condensed in the plume to disrupted unaltered material from the crust of the impactor, such as the hydrated matrix lumps. The occurrence of the hydrated matrix lumps, some of which have not been heated above 150 °C, together with the higher temperature components that formed above 1000 °C, is further evidence that they accreted together. Sweep-up would have occurred as the rotating impactor moved through the plume producing the layering: Isheyevo thus represents material accreted while that part of the rotating planetesimal moved into the plume. As such, the layers do not represent a continuous and uninterrupted accretion sequence; instead they record snap shots in time through the plume. These layers were then modified post sweep-up, but prior to compaction, producing the faults and load structures. The location on the parent-body, represented by the Isheyevo meteorite, may have accreted within a crater or other topographic low, and thus protected from surrounding impacts. In addition, debris from surrounding impacts may have buried the Isheyevo material to depths where later impacts caused post sedimentary compaction, metal deformation, and shock features, though it is difficult to disentangle shock features that may have occurred on the Isheyevo parent body, from those that occurred during its breakup.

Terrestrial laminated sediments are formed predominantly through the action of wind or water by the consolidation of loose particles that accumulate in layers, giving rise to the source-to-sink paradigm of terrestrial sedimentary systems. This model has been extended to processes that formed sediments on Mars, Venus, and Titan (Grotzinger et al., 2013). The

Isheyevo sediment provides a new example of “source-to-sink”, where instead of fluvial and aeolian processes, deposition from a plume in space onto a rotating planetesimal results in a stratigraphic record of layered sediment in the absence of atmosphere and under low gravity.

Isheyevo is the first in our extensive inventory of extraterrestrial samples to display laminated sedimentary structures and hence provides novel insights into early Solar System accretionary processes. The Isheyevo meteorite further illustrates the diversity of environments under which layered sediments can form in the Solar System.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

L.A.J.G was supported by [NASA](#) Origins of Solar System grant NNX11AK58G and Emerging Worlds grant NNX17AE56G. M.A.M. was supported by [NASA](#) Cosmochemistry grant NNX14AN58G and [NASA](#) Emerging Worlds grant NNX15AH62G. The authors are grateful to Dr. Marina Ivanova (Vernadsky Institute) and Dr. Martin Lee ([University of Glasgow](#)) for their insightful reviews that helped clarify and strengthen the paper.

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Fig. 1. Photograph of the polished slab of the Isheyev meteorite, ASU#1580_10, 421.0 g. Metal is white and silicates are black/grey. Individual silicate particles (chondrules, CAIs, and fine-grained lithic fragments) are visible as small dots. Centimeter scale at the bottom of the image. The contrast has been increased moderately to accentuate the sedimentary features. Areas 1–6 represent points discussed in the text.

Fig. 2.

False color image of slice ASU#1580_1, 234.1 g. The contrast has been boosted and the image tinted blue in order to accentuate the structural features as outlined by the variation in metal/silicate concentrations. Descriptions of the sedimentary Units A through G are given in the text. Red lines delineate the boundaries between the sedimentary units. The fault and shear zone are indicated by the white arrows and the offsets through Units B to D by the dotted yellow lines. The large thick white arrow at the top right of the image shows stratigraphic up in the sequence. (Larger image available as supplementary Fig. S4). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3.
Reflected-light image of a representative polished area of the Isheyevo meteorite showing metal (bright) and silicates (dark grey), and the prominent metal-metal grain boundaries.

Fig. 4.

Reflected-light image of a typical area of Isheyevo stained with potassium metabisulfite (top panel) and results of EPMA scans for Fe and Ni across four metal grains (A through D). The locations of the line scans are shown by the arrows across the four grains. Grains A and B are zoned Fe-Ni metal grains, C is decomposed into Ni-rich and -poor lamellae, and D is an unzoned kamacite grain. The staining reveals two additional zoned Fe-Ni grains at the bottom left of the panel and several unzoned light-blue-stained kamacite grains. Grey grains are unstained silicates. Section #ASU1580_B_2. (Larger image available as supplementary Fig. S5.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 5.

Images and EPMA data for a single elementally zoned Fe-Ni metal grain. **A)** Reflected-light image of the grain stained with potassium metabisulfite. The grain is stained blue around the edges and light tan in the center. The red arrow indicates the location of the EPMA line scan in panel **(B)**, showing the variation of Ni and Fe across the grain. **C)** Reflected-light microscope photograph of the same grain lightly etched with nital and imaged under Nomarski illumination. The kamacite rim is largely featureless, though Neumann bands are visible near the top of the grain. **D)** Higher magnification of the center of the grain in **(C)** showing the oriented submicron α_2 structure. Section #ASU1580_B_2. (Larger image available as supplementary Fig. S5.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 6.

Reflected-light photographs of Isheyevo stained with sodium bisulfite. The stain colors the metals shades of cream, tan, to blue, whereas the silicates are unstained and dark grey. **A)** Deformed zoned metal particle with an Ni-rich martensitic center (light tan) and kamacite rim (blue). The kamacite is deformed and shows an abundance of curved deformation bands (red arrows). These deformation bands do not extent into the martensitic core, which shows a parallel-banded structure. **B)** Edge of round chondrule (S-c) pushed into and deforming a metal grain composed of tetrataenite (white) and kamacite (tan). **C)** Kamacite (K) severely deformed along one edge and showing an abundance of deformation bands. **D)** Angular edge of a silicate grain (S) pressed into and deformed a kamacite grains. The deformation is evident by the Neumann bands (one indicated by the red arrows) running roughly N-S. The Neumann bands have a different color (light tan) compared to the host grain as the twin has a different orientation to the parent grain and stains a different color. The thin dark lines, some of which are curved, represent deformation bands (microbands and shear bands) formed by extensive plastic deformation of the impinging silicate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 7.

Measurements of the degree of flattening of metal particles in six areas (1–6) of slice ASU#1580_10. The angles for areas 1 through 4 were measured with the 0° parallel to the stratigraphic layering. Angles for areas 5 and 6, which are in the shear zone, were measured with the 0° parallel to the layering in adjacent area 4. The “n=” in each histogram represents the number of grains measured. Locations of areas 1–6 shown in Fig. 1.

Fig. 8. Measurements of the aspect ratios (major axis/minor axis) of metal grains from Areas 2 and 5.

Fig. 9.

Glass and fine-grained material between metal grains from ultrathin section

ASU#1580_A_1. **A)** Plane-polarized transmitted-light microscope image of an ultrathin section showing metal (black), silicates (clear), and metal-metal grain boundary material (orange). **B)** Reflected-light image of **(A)** showing the prominent metal-metal grain boundaries. **C)** Magnified area in **(A)** showing the orange metal-metal grain-boundary material. **D)** Same area as **(C)** imaged with reflected-light. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 10.

Reflected-light microscope images of a potassium bisulfite stained section showing (A) fine-grained material (red arrows) surrounding a chondrule (S-c). And (B) shock melt (red arrows) consisting of droplets of metal/sulfide embedded in silicate glass. The large melt pockets also has droplets of silicate embedded in the metal/sulfide. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)