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The Famenin fall and other ordinary chondrites intermediate between H and L groups

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3 1 **Title: The Famenin fall and other ordinary chondrites intermediate**
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5 2 **between H and L groups**
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25 **Abstract**

26 The Famenin meteorite fell around 08:30 am local time (GMT+4.5) on 27 June 2015
27 on the roof of a house in Famenin town, NW Iran. A single 640 grams stone was
28 recovered, shattered into several pieces upon impact. The shape of the impact hole and
29 the relative position of the recovered meteorites indicate a N-NW fall direction. Famenin
30 is an ordinary chondrite with well preserved chondrules of various types, (Fe,Ni) metal,
31 troilite, phosphate, and chromite. The organic matter systematics and the olivine and
32 low-Ca compositional distributions (percent mean deviations 18% and 31%,
33 respectively) indicate it is a type 3.4/3.8 chondrite. Considering the average chemical
34 compositions of olivine ($Fa_{17.5\pm 4.7}$) and low-Ca pyroxene ($Fs_{16.8\pm 7.5}$), average Co content
35 of the kamacite (5.6 mgg^{-1}), and Cu/Ni and Ga/Ni ratios, Famenin should be classified
36 as an H chondrite. However, saturation magnetization is $26.0 \text{ Am}^2/\text{kg}$, indicating a bulk
37 metal content similar to L chondrites. Similarly, the whole rock Ni and Co contents
38 (13073 and $540 \text{ } \mu\text{gg}^{-1}$, respectively), and average chondrule diameter ($550 \text{ } \mu\text{m}$) are
39 closer to typical values for L chondrites than H chondrites. The (Fe,Ni) metal modal
40 abundance (5 vol%), magnetic susceptibility, and possibly whole rock oxygen isotopic
41 composition indicate intermediate properties between H and L chondrites. Noble gas
42 composition and cosmic ray exposure (CRE) ages of Famenin and El Médano 195
43 (another intermediate ordinary chondrite) shows their gas-rich character and an older
44 ejection age from their parent body than those for the majority of H and L chondrites.
45 Famenin, together with similar intermediate ordinary chondrites, increases the diversity
46 of this meteorite clan and suggests the existence of a separate ordinary chondrite group
47 with a composition broadly intermediate between H and L groups for which a different
48 designation (HL) is proposed. Ordinary chondrites likely originate from more than three
49 parent bodies (H, L, and LL) as traditionally proposed.

50 **Keywords:** Fall, Intermediate chondrite, HL, ordinary chondrites, classification

54 INTRODUCTION

55 Around 08:30 am local time (GMT+4.5) on 27 June 2015, a meteorite fell in Famenin
56 town of Hamedan province (35° 7.12' N, 48°58.50' E) in Iran (Fig. S1). R. Salimi a
57 resident of the town, heard the sound of an impacting object onto the roof of his house.
58 He discovered that part of the roof was damaged and fragments of a stone were spread
59 on the roof and in the yard. The impact had damaged the asphalt layer of the roof.
60 Looking for the impactor, he found shattered fragments of the meteorite (Fig. 1). In
61 addition, another sample (~ 10 grams) was found resting on the floor of the neighbor's
62 house after breaking the window glass. The shape of the damaged roof and the relative
63 position of the meteorite indicates a N-NW fall direction (Fig. 1a). News of the event
64 propagated quickly via the local media. Despite additional searches by the locals, no
65 additional samples were collected. No record of related fireball sighting or atmospheric
66 detonation sounds were reported. Only two meteorite falls have been recorded in Iran
67 before Famenin: Veramin mesosiderite (Graham and Hassanzadeh 1990; Ward 1901)
68 and Naragh H6 chondrite (Adib and Liou 1979; Clarke 1975) fallen in 1880 and 1974,
69 respectively.

70 The Famenin meteorite was classified at CEREGE (Aix-en-Provence) as H/L3 (i.e. an
71 ordinary chondrite with intermediate properties between those of the H and L groups)
72 and published in the Meteoritical Bulletin (Bouvier et al. 2017). Ordinary chondrites
73 (OCs) with such intermediate characteristics are rare, and it has been suggested that
74 they form an individual group (Kallemeyn et al. 1989; Trigo-Rodríguez et al. 2009;
75 Wittmann et al. 2011). Tieschitz and Bremervörde are two H/L chondrites which have
76 been investigated by other workers and proposed to be representative samples of this
77 group.

78 As more work on new meteorites is being conducted, the meteorite classification
79 scheme is developing. This is evidenced by recent works describing meteorites that do
80 not belong to any of the recognized groups and that eventually form new groups (e.g.,
81 Weisberg et al. 2015; Pourkhorsandi et al. 2017; King et al. 2019; Metzler et al. 2021).
82 These studies reveal a diversity of solar system materials higher than previously

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3 83 assumed, mirroring the differences in physico-chemical conditions in the solar nebula
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5 84 and structures of meteorite parent bodies (Greenwood et al. 2020).
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7 85 In this work, we investigate the petrography, mineral chemistry, whole rock trace
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9 86 element, oxygen isotopic compositions, noble gas composition, and physical properties
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11 87 of Famenin. In addition, in an effort to characterize intermediate H/L OCs and
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13 88 understand their relationships with H and L groups, we compare Famenin with
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15 89 Bremervörde (H/L3), El Médano 195 (EM 195, H/L3), Gursum (H5), Pavel (H3-
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17 90 anomalous), and San Juan 041 (SJ 041, H/L6).
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19 91

20 92 **METHODOLOGY**

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23 93 Three polished thin and thick sections of Famenin and thick sections of EM 195,
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25 94 Pavel, Gursum, and SJ 041 were prepared for petrographic studies. Mineralogical and
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27 95 petrological studies were conducted with a Leica DM2500P optical microscope and a
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29 96 Hitachi S3000-N Scanning Electron Microscope (SEM) equipped with a Bruker X-ray
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31 97 Energy Dispersive Spectrometer (EDS) at CEREGE. Chemical compositions of the
32
33 98 mineral phases were determined with CAMECA SX50 and SX100 electron microprobes
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35 99 at the CAMPARIS facility (Paris). The operating conditions were focused electron beam
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37 100 (~ 1 μm in diameter), an accelerating voltage of 15 kV and a beam current of 10 nA.
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39 101 Both natural and synthetic standards were used for calibration: albite for Na; anorthite
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41 102 for Al; apatite for P; diopside for Mg, Si, Ca; orthoclase for K; pyrite for S; MnTiO₃ for
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43 103 Mn, Ti; Cr₂O₃ for Cr; Fe₂O₃ for Fe; NiO for Ni. For analyses of metallic phases, pure Ni,
44
45 104 Fe and Co were used as standards. In addition to synthetic standards, we analyzed
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47 105 (Fe,Ni) metal in several H chondrites (Agen, Catalina 396, and Taqtaq-e Rasoul), L
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49 106 chondrites (Andila and Djadjarm), and LL chondrites (Bensour) (Table S1). The
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51 107 agreement between chemical composition (Fe, Co, and Ni) of kamacite in these
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53 108 chondrites with the ranges reported for their corresponding groups was used to check
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55 109 the accuracy of our metal analysis. It should be noted that the measurement spots were
56
57 110 chosen randomly including both the core and rims of grains aiming to analyze areas
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59 111 with diverse chemical compositions.
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3 112 Magnetic measurements were performed at CEREGE. Magnetic susceptibility was
4 113 measured using a KLY2 instrument from Agico equipped with a large (65 cm³) or a
5 114 small (10 cm³) coil. Magnetic hysteresis properties were measured with a Princeton
6 115 Micromag vibrating sample magnetometer (VSM) with a noise level of about 1 nAm²
7 116 and a maximum applied field of 1 T. Hysteresis loops allow the determination of
8 117 coercivity (B_C), saturation magnetization (M_S), saturation remanent magnetization (M_{RS}),
9 118 (χ_{HF} , including both diamagnetic and paramagnetic contributions). Coercivity of
10 119 remanence (B_{CR}) was evaluated through DC back-field demagnetization of the
11 120 saturation remanence.
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19 121 The whole rock trace element content of Famenin was determined by Inductively
20 122 Coupled Plasma - Mass Spectrometry (ICP-MS) using a Perkin-Elmer NexION[®] 300x
21 123 spectrometer at the Pisa University's Dipartimento di Scienze della Terra. Allende
22 124 carbonaceous chondrite reference sample (USNM 3529, split 20, position 22) was
23 125 dissolved and analyzed along with Famenin to check the accuracy of the results. About
24 126 50-100 mg of each powder were dissolved in a mixture of HF and HNO₃ on a hot plate
25 127 at ~120 °C inside screw-top perfluoroalkoxy (PFA) vessels. Then the sample solutions
26 128 were diluted to 50 mL in polypropylene vials. In each step of sample preparation, Mill-
27 129 Q[®] purified water (18.2 M cm), ultrapure HF and HNO₃ were used. The sample solutions
28 130 were introduced into the plasma after online mixing with a solution containing 20 ng/mL
29 131 each of Rh, Re and Bi as internal standards. The elements Li, Be, Ni, Co, Ga, Rb, Sr, Y,
30 132 Zr, Nb, , Cs, Ba, REE, Hf, Ta, W, Pb, Th, U were determined in "standard mode",
31 133 whereas the elements Sc, Cu, Zn were determined in "kinetic energy discrimination
32 134 mode, KED" using a He flow of 3.7 mL/min. Analyses were done using an external
33 135 calibration performed with a solution of the BE-N (alkaline basalt) geochemical
34 136 reference sample. In **Table 1** the results of the ICP-MS analyses of Allende along with
35 137 the literature values are reported. The analytical precision is between 5 and 10% RSD
36 138 for elements with concentrations > 0.5 µg/g and between 10 and 20% RSD for elements
37 139 with concentrations < 0.5 µg/g.
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53 140 Measurements of $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ of two Famenin 1.5 mg aliquot of silicates hand-
54 141 picked from a powdered and acid-washed 200 mg bulk sample were carried out at the
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3 142 Stable Isotopes Laboratory of CEREGE. Laser fluorination coupled with isotope ratio
4 143 mass spectrometry (IRMS) (Alexandre et al., 2006; Crespin et al., 2008) adapted for
5 144 measurement of extraterrestrial materials (Suavet et al. 2010) was used for this
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7 145 purpose. The three oxygen isotopic compositions were measured with a dual-inlet mass
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9 146 spectrometer Thermo-Finnigan Delta Plus. In addition to Famenin, we analyzed 1.5 mg
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11 147 samples of Bremervörde (H/L3), EM 195 (H/L3), Gursum (H5), Pavel (H3-anomalous),
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13 148 SJ 041 (H/L6) as well as Ochansk (H4), Paranaiba (L6), and Homestead (L5), as
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15 149 example of regular ordinary chondrites. The initial bulk sample was powdered, sieved
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17 150 between 100 and 400 μm , cleaned with 1M HCl at 50°C for several hours to remove
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19 151 metal and sulfides, and rinsed with ethanol. Additional leaching with mono-
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21 152 ethanolamine-thioglycolate (EATG) was performed for weathered finds, to remove
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23 153 oxyhydroxides formed during weathering on Earth (see Greenwood et al. 2017 for the
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25 154 use of EATG in this context). The average mass of the initial bulk samples was 73 mg,
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27 155 ensuring that the 1.5 mg aliquot is representative of the bulk oxygen isotopic
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29 156 composition. The oxygen isotope results are expressed in ‰ versus the international
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31 157 reference standard V-SMOW: $\delta^{18}\text{O} = [({}^{18}\text{O}/{}^{16}\text{O})_{\text{sample}}/({}^{18}\text{O}/{}^{16}\text{O})_{\text{V-SMOW}} - 1] \times 1000$ and $\delta^{17}\text{O}$
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33 158 $= [({}^{17}\text{O}/{}^{16}\text{O})_{\text{sample}}/({}^{17}\text{O}/{}^{16}\text{O})_{\text{V-SMOW}} - 1] \times 1000$. The $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ values of the reference
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35 159 gas were calibrated with measurements of NBS28 standard ($\delta^{18}\text{O} = 9.60\text{‰}$, Gröning,
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37 160 2004). $\Delta^{17}\text{O}$ is computed as $\Delta^{17}\text{O} = \delta^{17}\text{O} - 0.52 \times \delta^{18}\text{O}$. The $\delta^{17}\text{O}$ value of the NBS28
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39 161 standard ($\delta^{17}\text{O} = 4.992\text{‰}$) was computed so as to give $\Delta^{17}\text{O} = 0\text{‰}$. The measurements
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41 162 were corrected on a daily basis using 1.5 mg quartz internal laboratory standard
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43 163 “Boulangé” (Alexandre et al. 2006; Suavet et al. 2010). During the analyzing period, the
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45 164 analytical uncertainties (1σ) derived from repeated measurement ($n = 7$) of this internal
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47 165 laboratory standard are 0.10‰, 0.16‰, 0.02‰ for $\delta^{17}\text{O}$, $\delta^{18}\text{O}$ and $\Delta^{17}\text{O}$, respectively.

45 166 The Raman spectroscopy was performed at Laboratoire de Géologie de Lyon Terre,
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47 167 Planètes, Environnement (ENS Lyon) with a Labram spectrometer (Horiba-Jobin-Yvon)
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49 168 equipped with a Spectra Physics Argon ion laser and using 514.5 nm excitation.
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51 169 Carbonaceous matter is sensitive to laser-induced heating and can be locally altered.
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53 170 Moreover, the Raman bands of the polyaromatic carbonaceous matter are dispersive.
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55 171 Thus, to avoid any laser alteration of the carbonaceous matter and to have a meaningful
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57 172 comparison with reference meteorites from the literature, the same experimental and

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3 173 analytical conditions as in Bonal et al. (2016) were used. Raman spectra of the
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5 174 carbonaceous matter in Famenin were obtained both on isolated matrix grains and in-situ
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7 175 in a polished section. A raw piece of approximately 200 mg was gently crushed. Around
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9 176 30 matrix fragments (typical apparent diameter around 30 μm) were then manually
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11 177 selected according to their color and texture under a binocular microscope. The selected
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13 178 matrix fragments were pressed between two glass slides that were also used as substrate
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15 179 for the Raman analysis. This procedure allows working on “fresh” samples and helps
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17 180 enhance heat dissipation, thereby minimizing thermal damage. Measurements made
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19 181 over two different sessions on two aliquots provided similar results.

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21 182 Gamma spectroscopy and intensity measurements of ^7Be , ^{54}Mn , ^{22}Na , and ^{26}Al of the
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23 183 two larger fragments (total ~ 23 g) were carried out from 16 to 24 July 2015 (683500
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25 184 seconds) in LSCE (Gif-sur-Yvette, France).

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27 185 The noble gas concentrations and isotopic ratios ($^3,^4\text{He}$, $^{20,21,22}\text{Ne}$, and $^{36,38,40}\text{Ar}$) of
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29 186 EM 195, SJ 041, and Famenin were measured using a Noblesse (Nu) multi-collector
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31 187 noble gas mass spectrometer in the noble gas laboratory at the Institute of Geology and
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33 188 Geophysics, Chinese Academy of Sciences, Beijing, China. The analytical approach
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35 189 follows the same procedures as described in Ranjith et al. (2017). Briefly, samples with
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37 190 masses ranging from ~ 3 to ~ 5 mg were first washed with ethanol in an ultrasonic bath,
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39 191 weighed, and then loaded into the laser sample chamber of the noble gas extraction
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41 192 and purification line. The He standard is the “He Standard of Japan” (“HESJ”), with a
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43 193 calibrated $^3\text{He}/^4\text{He}$ ratio of 20.6 ± 0.1 Ra (Matsuda et al. 2002), where Ra stands for the
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45 194 $^3\text{He}/^4\text{He}$ ratio of air (i.e. 1.4×10^{-6}). The average sensitivities for ^4He , ^{22}Ne , and ^{36}Ar are,
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47 195 in units of $\text{cm}^3\text{STP}/\text{counts}$, 3.67×10^{-15} , 3.17×10^{-15} , and 4.26×10^{-16} , respectively. Blanks
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49 196 were frequently measured using the exact same procedure as for the samples (see
50
51 197 details below). They contribute for less than 1% for He, less than 2% for Ne, and less
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53 198 than 5% for Ar isotopes. Noble gases have been extracted by heating the samples in a
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55 199 single extraction step, using a CO_2 laser (1.064 μm wavelength, 3 mm diameter) for ~ 30
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57 200 minutes. The released gases were cleaned from all reactive gases such as
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59 201 hydrocarbons, etc. using a series of getters, operating at room temperature and 200°C
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202 (Ranjith et al. 2017). The He-Ne fraction is separated from the Ar fraction using an
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activated charcoal held at the temperature of liquid nitrogen (LN_2) for 20 minutes.

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3 204 Subsequently, the Ne is separated from the remaining He by using a cryogenic cold trap
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5 205 at 35K for 10 minutes. A fraction of the He gas is then inlet into the mass spectrometer.
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7 206 The Ne fraction is released at 80K for 30 minutes and the total gas fraction is inlet into
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9 207 the mass spectrometer; remaining background gases, such as hydrocarbons and Ar,
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11 208 which would compromise the Ne measurements, are further reduced using a charcoal
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13 209 held at LN₂ temperature during the Ne measurements. Finally, Ar is released at ~150°C
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15 210 for 20 minutes, and a known fraction of the gas is measured.
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212 **RESULTS**

213 **Macroscopic description**

214 Upon the impact on the ground, the Famenin meteorite fragmented into two large
215 and eight small pieces. The total recovered mass is 630 g. The two larger pieces total
216 565 g while the smaller fragments have masses between 5 and 25 g (Fig. 1). Famenin
217 has weakly developed regmaglypts and the fusion crust has a black to dark-brown color
218 with shiny patches of glassy material covering the fusion crust as an additional layer.
219 The remnants of roofing asphalt material can be seen as black patches with sizes up to
220 5 cm.

221 The meteorite broken surface reveals a light grey interior. Distinct chondrules, (Fe,Ni)
222 metal and troilite are easily discernible with the naked eye. (Fe,Ni) metal grains show no
223 sign of weathering. A few fine-grained mm to cm-sized clasts with light lithology are also
224 visible (Fig. 1b), although they were not present in the studied type specimen.

225 **Optical and electron microscopy**

226 *Famenin*

227 The fusion crust shows a vesicular texture with magnetite grains in the outermost
228 layer and thin troilite veinlets formed by melting and recrystallization of the primary
229 troilite during atmospheric passage of the meteoroid (Fig. 2, 3a). Point counting of a ~
230 10 cm² surface under reflected light optical microscopy, with a step-size of 50 μm, yields
231 the following proportions: 90.0 vol% silicates, 5.0 vol% (Fe,Ni) metal, and 5.0 vol%

troilite (n = 584). Barred olivine, cryptocrystalline, porphyritic, and radial pyroxene chondrule types are present (Fig. 2, 3). The average apparent chondrule diameter is $550 \pm 296 \mu\text{m}$ (1σ ; n = 100), with a median, mode, and maximum diameters of 510, 360, and 1960 μm , respectively (Fig. 4). Backscattered electron (BSE) images of the Famenin chondrite are shown in Fig. 3b-g. Olivine and pyroxene are not completely equilibrated and show a normal zoning with higher Fe (and lower Mg) in mineral rims than in mineral cores. Overall, olivine is more homogeneous than pyroxene. The matrix is mostly clastic and comprises individual (Fe,Mg) silicates and chondrule fragments. (Fe,Ni) metal and troilite are not completely separated from each other. Compared to troilite, most of the (Fe,Ni) metal grains are relatively rounded. Opaque rims consisting mostly of troilite aggregated with (Fe,Ni) metal and (Fe,Mg) silicates surround some of the chondrules. Fig. 3-g shows a barred olivine chondrule with normal zoning containing dendritic clinopyroxene crystallized out of the felsic mesostasis. Olivine exhibits undulatory extinction and displays planar fractures with about 200 μm spacing. Troilite displays finely polycrystalline textures with domain size of about 10 μm (Fig. 3h).

247 *El Médano 195*

248 EM 195 is a find classified as H/L3 (Ruzicka et al. 2015). A mosaic image is shown in
249 Fig. S2. Point counting of a $\sim 1.2 \text{ cm}^2$ surface under reflected light optical microscopy,
250 with a step-size of 80 μm , yields the following proportions: 79.0 vol% silicates, 9.0 vol%
251 (Fe,Ni) metal, and 12.0 vol% troilite (n = 531). Most (Fe,Ni) metal and troilite grains are
252 in contact with each other. Troilite rims around chondrules are preserved and few
253 (Fe,Ni) metal globules are present. Average apparent chondrule diameter is 570 ± 331
254 μm (1σ ; n = 84), with a median, mode, and maximum diameters of 480, 426, and 1970
255 μm , respectively (Fig. 4). The abundance of the weathering products is low with only
256 thin rims of Fe oxides/oxyhydroxides around few (Fe,Ni) metal grains, indicating a
257 weathering grade W1 (Wlotzka 1993).

258 *San Juan 041*

259 SJ 041 is a find classified as H/L6 (Garvie 2012). Thermal metamorphism has led to
260 the recrystallization of chondrules and the separation of (Fe,Ni) metal and troilite from
261 each other (Fig. S3). Elongation of the (Fe,Ni) metal and troilite and the presence of

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3 262 melt pockets containing troilite droplets indicates that SJ 041 is heavily shocked. Point
4 263 counting under reflected light optical microscopy, with a step-size of 80 μm , yields the
5 264 following proportions: 84 vol% silicates, 7 vol% (Fe,Ni) metal, and 8 vol% troilite ($n =$
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7 601). The meteorite has a weathering grade W2.
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10 266 *Pavel*

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13 267 Pavel is a fall, classified as a H5. However, Dekov et al. (2017) proposed
14 268 reclassification as H3-anomalous. The thick section used in present study is the same
15 269 as used by Dekov et al. (2017). A mosaic image is shown in Fig. S4. Pavel has a well-
16 270 defined chondrules with average apparent diameter of $485 \pm 186 \mu\text{m}$ (1σ ; $n = 33$) in
17 271 agreement with measurements by Dekov et al. (2017), with a median, mode, and
18 272 maximum diameters of 440, 400, and 840 μm . (Fe,Ni) metal and troilite grains are
19 273 devoid of any alteration evidences (weathering grade W0).

24 274 **Mineral chemistry**

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27
28 275 The representative chemical compositions of olivine, low-Ca pyroxenes, and (Fe,Ni)
29 276 metal in Famenin are reported in Table 2 and 3. Low-Ca pyroxenes show a wider
30 277 composition range than the olivine (Fs_{0.7-36.6} vs. Fa_{5.9-30.9}) (Fig. 5). The percent
31 278 mean deviations (PMD) are 31% and 18% for low-Ca pyroxene and olivine,
32 279 respectively. Average olivine and low-Ca pyroxene compositions are Fa_{17.5 \pm 4.7} ($n = 71$)
33 280 and Fs_{16.8 \pm 7.5}Wo_{4.3 \pm 5.9} ($n = 35$), respectively. The average Co concentration of kamacite
34 281 is $4.7 \pm 2.0 \text{ mg/g}$ ($n = 23$, Table 3).

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37 282 For EM 195, representative chemical compositions of olivine and low-Ca pyroxene
38 283 are reported in Table 2. For EM 195, PMD for olivine and low-Ca pyroxene is 29% and
39 284 23%, respectively. The average Co concentration of kamacite is $3.8 \pm 1.0 \text{ mg/g}$ ($n = 23$,
40 285 Table 3).

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42
43 286 In accordance with the equilibrated texture, the mineral composition of olivine and
44 287 low-Ca pyroxene of SJ 041 shows a narrow distribution (Table 2). PMD for olivine and
45 288 low-Ca pyroxene is 0.8% and 3.5%, respectively. Average olivine and low-Ca pyroxene
46 289 compositions are Fa_{22.5 \pm 0.2} ($n = 4$) and Fs_{18.3 \pm 0.8}Wo_{1.1 \pm 0.9} ($n = 5$), respectively. The
47 290 average Co content of kamacite is $5.9 \pm 0.9 \text{ mg/g}$ ($n = 24$).

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3 291 Gursum an H4/5 (Graham 1983), later reclassified as an H5 by Schultz et al. (1990),
4 292 has average olivine and low-Ca pyroxene compositions of $Fa_{16.0\pm 0.3}$ (n =5) and
5 293 $Fs_{14.2\pm 0.2}Wo_{1.3\pm 0.1}$ (n = 6), respectively (Table 2). Cobalt concentration of kamacite in this
6 294 chondrite is 3.42 ± 1.1 mg/g (n = 24, Table 3).

295 **Magnetic properties**

13 296 The average magnetic susceptibility of Famenin measured on four pieces with
14 297 masses in the range 5 - 11 grams is $\log\chi = 5.07 \pm 0.05$ (1σ) with χ in $10^{-9} \text{ m}^3\text{kg}^{-1}$.
16 298 Saturation magnetization measured on a 80 mg fragment is $M_S = 24.9 \text{ Am}^2\text{kg}^{-1}$.
18 299 Hysteresis parameter ratios are $M_{RS}/M_S = 1.02 \times 10^{-2}$ and $B_{CR}/B_C = 26.5$.

20 300 The magnetic susceptibilities of EM 195 (W1) and SJ 041 (W2) are $\log\chi = 4.99$ and
22 301 $\log\chi = 4.59$, respectively.

25 302 **Trace element bulk chemistry**

27 303 The whole rock trace element composition of Famenin is reported in Table 1. CI-
28 304 normalized spider diagrams of Famenin along with the mean values reported for H, L,
30 305 and LL OCs (Wasson and Kallemeyn 1988) are shown in Fig. 6. Trace element content
32 306 of Famenin is chondritic and it follows the general trend of OCs. Some highly volatile
34 307 elements such as Rb, Li, Pb, and Ga in Famenin and OCs follow a similar enrichment
35 308 and depletion patterns in relation to mean CI chondrites. However, Cs content in
37 309 Famenin is closer to mean LL values than H and L chondrites. Lower concentrations of
38 310 Ba and Be and higher Sr and Nb in Famenin compared to the OCs are other noticeable
40 311 differences between them. Besides differences in absolute concentrations, deviations
42 312 also exist in elemental ratios such as Sr/Ba which is 4.4, higher than the mean value for
44 313 H (2.4), L (3.0), and LL (2.3) chondrites.

47 314 **Oxygen isotopic composition**

49 315 The whole rock oxygen isotopic composition analysis results for two aliquots of
50 316 Famenin along with the data for other H, L, and intermediate ordinary chondrites that we
52 317 analyzed are reported in the Table 4. Fig. 7 depicts the $\Delta^{17}\text{O}$ versus $\delta^{18}\text{O}$ values of
54 318 Famenin along with the data for H, L, LL, and H/L chondrites. Literature data for

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3 319 ordinary chondrites are compiled in **Table 2S**. Our test samples Homestead, Ochansk,
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5 320 and Paranaiba plot in the range of their respective chondrite groups. Our $\Delta^{17}\text{O}$ values of
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7 321 1.00‰ and 0.97‰ (average 0.98‰) for Famenin, and 0.96‰ for Bremervörde, are in
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9 322 the very low range for L chondrites. They also show slightly higher $\delta^{18}\text{O}$ values than the
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11 323 majority of L chondrites and plot in the close vicinity of Tieschitz H/L chondrite (analyzed
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13 324 by Clayton and Mayeda 1991). SJ 041 with a $\Delta^{17}\text{O}$ of 1.02‰ with a higher $\delta^{18}\text{O}$ is also
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15 325 close to them. Pavel has a $\Delta^{17}\text{O}$ similar to H chondrites, however its $\delta^{18}\text{O}$ is more than
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17 326 one permil higher than most of them. EM 195 plots in the range of type 3 L chondrites.
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19 327 Officially classified as an H chondrite, Gursum has an oxygen isotopic composition
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21 328 similar to equilibrated L chondrites.

21 329 **Organic matter**

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23 330 Each individual Raman spectra obtained on matrix of Famenin exhibits the D- and G-
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25 331 bands, attesting the presence of polyaromatic carbonaceous matter. Spectral differences
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27 332 (e.g., shape, relative intensity...) are visible on the raw Raman spectra, reflecting variable
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29 333 structural order of the polyaromatic carbonaceous matter within Famenin. These
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31 334 differences are confirmed by the range of spectral parameters obtained through the
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33 335 analytical adjustment. Spectral parameters of Famenin are variable but tend to be
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35 336 distributed among two main groups with the following mean values:

36 337 Famenin (A): FWHM_D (cm^{-1}) = 151.8 ± 17.2 ($n = 15$) and $I_D/I_G = 1.03 \pm 0.06$

37 338 Famenin (B): FWHM_D (cm^{-1}) = 56.2 ± 13.6 ($n = 15$) and $I_D/I_G = 1.13 \pm 0.21$

39 339 Spectra acquired on manually selected matrix grains are both of type “A” and “B”.
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41 340 However, this variability is not easily discernible in *in-situ* measurement data. Deciding
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43 341 whether the observed variability in bulk data results from brecciation is not possible based
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45 342 on available data.

46 343 **Cosmogenic nuclides**

47 344 *Short-lived isotopes*

49 345 The data show the presence of ^7Be ($t_{1/2} = \sim 53$ days; 477 keV), ^{54}Mn ($t_{1/2} = \sim 312$ days;
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51 346 834.8 keV), ^{22}Na ($t_{1/2} = \sim 2.6$ years; 1274.5 keV) and ^{26}Al ($t_{1/2} = 7.17 \times 10^5$ years;
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53 347 1808.65 keV). The detection of short-lived nuclides such as ^7Be and ^{54}Mn and the
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55 348 detailed reports in the media confirm the occurrence of this fall event.

349 *Noble gas concentrations and isotopic ratios*

350 The measured isotopic noble gas concentrations of the three chondrites corrected
 351 from interferences from H_2O^+ , $^{40}\text{Ar}^{++}$, and CO_2^{++} (on Ne isotopes) and for instrumental
 352 mass discrimination are presented in **Table 5**.

353 The cosmogenic Ne concentrations and isotopic ratios (index “cos”) have been
 354 calculated and are reported in **Table 6**; To calculate the cosmogenic Ne concentrations
 355 and isotopic ratios in Famenin, we estimate Ne is a mixture between cosmogenic and
 356 SW endmembers (“SW” index). We assume $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{SW}}=13.78\pm 0.03$ and
 357 $(^{21}\text{Ne}/^{22}\text{Ne})_{\text{SW}}=0.0329\pm 0.0001$ (Heber et al. 2009) as the SW endmember. To calculate
 358 the cosmogenic Ne concentrations and isotopic ratios in EM 195, we estimate a mixture
 359 between three endmembers: cosmogenic, SW, and air, the latter being characterized by
 360 $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{air}}=9.80$ and $(^{21}\text{Ne}/^{22}\text{Ne})_{\text{air}}=0.029$. And $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{cos}}=0.82$ and
 361 $(^{21}\text{Ne}/^{22}\text{Ne})_{\text{cos}}=0.89$ corresponding to the measured concentrations in SJ 041 (**Fig. 8**).
 362 The determined cosmogenic ratios $(^{22}\text{Ne}/^{21}\text{Ne})_{\text{cos}}$ vary between 1.12 for SJ 041, and
 363 1.95-2.52 for EM 195 and Famenin.

364 The measured $^{36}\text{Ar}/^{38}\text{Ar}$ and $^{40}\text{Ar}/^{36}\text{Ar}$ range from 3.96-5.04 and 90-535, respectively.
 365 In order to calculate the amount of cosmogenic $^{36}\text{Ar}_{\text{cos}}$ and $^{38}\text{Ar}_{\text{cos}}$, we used a three-
 366 component deconvolution assuming that the isotopic compositions are a mixture
 367 between cosmogenic, air, and SW endmembers. We used the following
 368 $(^{36}\text{Ar}/^{38}\text{Ar})_{\text{cos}}=0.63$, $(^{36}\text{Ar}/^{38}\text{Ar})_{\text{air}}=5.32$, and $(^{36}\text{Ar}/^{38}\text{Ar})_{\text{SW}}=5.47$. The cosmogenic $^{36}\text{Ar}_{\text{cos}}$
 369 and $^{38}\text{Ar}_{\text{cos}}$ concentrations are reported in **Table 6**.

370 *Cosmic-ray exposure ages*

371 The CRE ages (**Table 7**) have been calculated using the concentrations in
 372 cosmogenic $^3\text{He}_{\text{cos}}$, $^{21}\text{Ne}_{\text{cos}}$, and $^{38}\text{Ar}_{\text{cos}}$, later labelled T_3 , T_{21} , and T_{38} , as described in
 373 e.g. Li et al. (2017) and using correlations given by (Eugster 1988). Based on these
 374 assumptions, CRE ages range from 4.99-8.71 Ma for SJ 041, with the common trend
 375 $T_3 < T_{21} < T_{38}$, from 17.7-59.2 Ma for EM 195, and finally from 47.4-66.4 Ma for Famenin.
 376 Note that due to large discrepancies (most likely due to production rate calculation
 377 issues and/or He diffusive losses), we did not report the ^3He CRE ages T_3 for EM 195
 378 and Famenin. In addition, for these two chondrites, we observe that the calculated T_{38}
 379 ages are systematically lower than T_{21} .

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5 381 **DISCUSSION**6
7 382 **Classification of Famenin**

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10 383 Considering its mineralogy, bulk rock chemical composition, low abundance of matrix,
11 384 and oxygen isotopic composition, Famenin is undoubtedly an ordinary chondrite, but it
12 385 shares properties with both H and L chondrites, making its classification problematic. Its
13 386 average chondrule size is closer to the value for L chondrites than for H chondrites
14 387 (Metzler et al. 2018). On the other hand, average olivine and low-Ca pyroxene
15 388 compositions are $Fa_{17.5\pm 4.7}$ ($n = 71$) and $Fs_{16.8\pm 7.5}Wo_{4.3\pm 5.9}$ ($n = 35$), respectively, in the
16 389 range of H chondrites values (Fig. 9) (Bearley and Jones, 1998). Oxygen isotopic bulk
17 390 composition of Famenin is different from values measured in H chondrites (Fig. 7). Its
18 391 $\Delta^{17}O$ is in the low range for L chondrites; however, $\delta^{18}O$ is higher in Famenin and is closer
19 392 to the field of Tieschitz and Bremervörde H/L chondrites. The mean Co content in
20 393 kamacite (4.7 mg/mg) is in the range of values reported for H chondrites (4.4-5.1 mg/g)
21 394 (Fig. 10) (Afiattalab and Wasson 1980; Rubin 1990). The modal (Fe,Ni) metal abundance
22 395 in Famenin is lower than the average H chondrite values (5 vol% versus 8 vol%)
23 396 (Weisberg et al. 2006). Magnetic susceptibility χ and saturation magnetization (M_s) are
24 397 other proxies to the bulk metal content, and can be used for the classification of meteorites
25 398 (Rochette et al. 2003; Gattacceca et al. 2014). Magnetic susceptibility of Famenin ($\log\chi$
26 399 = 5.07) is intermediate between H (5.32 ± 0.10 , $n = 145$ falls) and L chondrites ($4.87 \pm$
27 400 0.10 , $n = 144$ falls), and similar to the magnetic susceptibility of Tieschitz (4.97) and
28 401 Bremervörde (4.98) H/L chondrites (Rochette et al. 2003). Saturation magnetization of
29 402 Famenin ($M_s = 24.9 \text{ Am}^2\text{kg}^{-1}$) is in the range of values reported in Gattacceca et al. (2014)
30 403 for L3 and L4 chondrites falls ($22.1\pm 5.1 \text{ Am}^2\text{kg}^{-1}$, $N = 7$) and much lower than the values
31 404 for H3 and H4 falls ($44.8\pm 4.5 \text{ Am}^2\text{kg}^{-1}$, $N = 8$). Hysteresis parameter ratios are similar to
32 405 the values observed in L and H chondrites, reflecting a combination of kamacite and
33 406 taenite (Fig. S5). With a Ni content of 13.1 mg/g compared to the average values of H
34 407 (16.0 mg/g), L (12.0 mg/g), and LL (10.2 mg/g) chondrites, Famenin is closer to the L
35 408 chondrite range (Fig. 11a,b). Its bulk Co content is 540 $\mu\text{g/g}$, which compared to the
36 409 average values of H (810 $\mu\text{g/g}$), L (590 $\mu\text{g/g}$) and LL (490 $\mu\text{g/g}$) chondrites, lies in between
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3 410 L and LL chondrites (Wasson and Kallemeyn 1988) (Fig. 11b). Same applies for the Ga
4 411 content (4.9 $\mu\text{g/g}$), in relation to mean H (6 $\mu\text{g/g}$), L (5.7 $\mu\text{g/g}$) and L (5 $\mu\text{g/g}$) chondrites
5 412 (Fig. 6S) and as well as W which is closer to mean L chondrites (Fig. 6) However, when
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7 413 we consider the Cu/Ni and Ga/Ni ratios (Fig. 11c,d), which are known to increase from H
8 414 to LL chondrites (Wasson and Kallemeyn 1988), Famenin falls in the range of H
9 415 chondrites. Considering these evidences, we classify Famenin as a meteorite
10 416 intermediate between H and L chondrites.

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15 417 The observed Raman spectral parameters scatter reflects variable thermal
16 418 metamorphism experienced by Famenin: type "A" spectra reflect thermal metamorphism
17 419 comparable to that experienced by type 3.4 chondrites, while type "B" spectra reflect a
18 420 higher thermal metamorphism (>3.7) (Fig. 12). It has to be noted that the type "A" spectra
19 421 are internally quite variable as well, with spectral parameters of individual spectrum
20 422 distributed over the metamorphic range observed in Bishunpur (3.1) to Tieschitz (3.6).
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22 423 This can be related to the structural grade of the polyaromatic carbonaceous matter which
23 424 reveals variable degrees of thermal metamorphism in different parts of the meteorite. The
24 425 PMD of olivine Fa content is 18%, indicating a petrologic type 3.8 (Sears et al. 1980), in
25 426 broad agreement with data obtained by Raman spectroscopy (type "B" spectra). Based
26 427 on these observations, we classify Famenin as a petrologic type 3 chondrite in the 3.4 to
27 428 3.8 range (Sears et al. 1980; 1982).

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29 429 Based on the olivine optical microscopy, and using the classification of Stöffler et al.
30 430 (2018), Famenin is very weakly shocked (S2 shock stage). However, random troilite
31 431 polycrystalline texture in some parts (Fig. 3h) might suggest a higher shock degree
32 432 (Ruzicka and Hugo 2018). Even though we did not study the two clasts visible in Fig. 1b
33 433 in detail, but the macroscopic studies by us and (McCausland et al., 2016),
34 434 heterogeneity observed in Raman spectroscopy data, and the noble gas compositions
35 435 of Famenin favors its classification as a breccia. It should be mentioned that as the
36 436 mentioned clasts are small relative to the bulk meteorite, in agreement with McCausland
37 437 et al. (2016), we believe that they would not affect our main conclusions regarding
38 438 Famenin's intermediate properties.

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54 439 Putting all these data together, we classify Famenin as an H/L3 (S2) brecciated
55 440 chondrite.

441 Gas compositions

442 With a $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of 0.82, we assume that Ne in SJ 041 is almost entirely
443 cosmogenic (with $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{cos}} \sim 0.80$, e.g., Leya et al., 2013). However, the measured
444 $^{20}\text{Ne}/^{22}\text{Ne}$ ratios of 9.27 and 12.45 for EM 95 and Famenin, respectively, indicate that, in
445 addition to cosmogenic noble gases, there is as well a contribution from a trapped
446 component, here likely a solar wind (SW) contribution. The solar Ne isotopic ratios in
447 meteorites are always distinct from the pure SW signature with $^{20}\text{Ne}/^{22}\text{Ne} = 13.7$ due to
448 fractionation processes. The measured $^{21}\text{Ne}/^{22}\text{Ne}$ ratios vary between 0.097 - 0.19 for
449 Famenin and EM 195, respectively. These data are in relatively good agreement with
450 previous observations for other gas-rich meteorites, and consistent with a SW influence
451 (Talahito and Keisuke 2006; Leya et al. 2009). The Ne three-isotope plot (Fig. 8) shows
452 the Ne isotopic data (blank- and fractionation-corrected) for EM 195 and Famenin. The
453 Ne isotopic ratios from SW, from solar cosmic-ray production (SCR-Ne), from galactic
454 cosmic-ray production (GCR-Ne) and from air are also shown. From this plot, two
455 important observations can be made. First, one can notice that the Ne isotopic
456 composition of Famenin is a clear mixture between a cosmogenic component (here
457 GCR-Ne) and SW; second, it appears the isotopic composition of EM 195 is a mixture
458 between three components: cosmogenic, SW, and air. This is not surprising as EM 195
459 is a find which has been subjected to hot desert weathering and influenced by
460 atmospheric contamination.

461 The range of $^{36}\text{Ar}/^{38}\text{Ar}$ ratios clearly indicate the presence of a trapped component,
462 most likely atmospheric (SJ 041) and/or SW (presumably for EM 195 and Famenin).
463 The composition of the bulk SW, measured by Genesis is $(^{36}\text{Ar}/^{38}\text{Ar})_{\text{SW}} = 5.47 \pm 0.01$
464 (Heber et al. 2009); given the fact that only two Ar isotopes can be dominated by solar
465 signature (i.e. $^{36,38}\text{Ar}$, ^{40}Ar is mainly radiogenic and dominated by decay of ^{40}K), an Ar
466 three-isotope plot would not, unlike Ne, help to decipher the Ar endmember
467 contributions (e.g. Rao et al. 1991).

468 Our gas data suggests that EM 195 and Famenin belong to a group of meteorites
469 called “gas-rich” meteorites, i.e., meteorites that contain large amounts of primordial
470 noble gases. Noble gas isotope records in gas-rich meteorites are explained by an

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3 471 incorporation of gases produced by solar wind (SW) radiations (Suess et al. 1964), for a
4 472 short period over few million years (Osawa and Nagao 2006). Gas-rich meteorites are
5 473 as well characterized by $^4\text{He} \geq 10^{-4} \text{ cm}^3\text{STP/g}$ (Megruie and Steinbrunn 1971). This is the
6 474 case for Famenin, with ^4He concentration of $3.0 \times 10^{-4} \text{ cm}^3\text{STP/g}$ (see Table 5). The
7 475 isotopic $^4\text{He}/^3\text{He}$ ratios for EM 195 and Famenin are 1503 and 3061, respectively. For
8 476 comparison, the $(^4\text{He}/^3\text{He})_{\text{SW}}$ is 2155 (Heber et al. 2009). However, the Solar Flare (SF)
9 477 He obtained by Rao et al. (1991) is close to $(^4\text{He}/^3\text{He})_{\text{SF}} = 3800 \pm 200$. We assume here
10 478 that ^3He is entirely cosmogenic.

11 479 In Fig. 1b, one can observe the presence of mm to cm clasts, indicating that EM 195
12 480 (Fig. S2) and Famenin are breccias. In addition, as mentioned above and as shown in
13 481 Table 5, EM 195 and Famenin contain solar-wind implanted noble gases, with e.g.,
14 482 $^{20}\text{Ne}/^{22}\text{Ne}$ ratios of 9.27 and 12.45, respectively. Note that the solar $^{20}\text{Ne}/^{22}\text{Ne}$
15 483 endmember of 12.45 measured for Famenin is in really good agreement with the range
16 484 of values of e.g., 11.6 - 11.9 in Fayetteville (Wieler et al., 1989) or 12.4 in Frontier
17 485 Mountain 90174 (Leya et al., 2009). This clearly indicates that EM 195 and Famenin
18 486 were exposed as a regolith before their compaction and are regolith breccias.

19 487 Based on the quality assignments in Graf and Marti (1995), both meteorites have
20 488 $^{20}\text{Ne}/^{22}\text{Ne}$ ratios which exceed the required conditions (i.e., $^{20}\text{Ne}/^{22}\text{Ne} > 2$; $^{36}\text{Ar}/^{38}\text{Ar}$
21 489 > 4.39) defined by the authors. Based on their work, only meaningful cosmogenic
22 490 concentrations and hence CRE ages can be calculated if the uncertainties due to the
23 491 corrections of the trapped component are moderate. This is obviously not the case for
24 492 both EM 195 and Famenin, with $^{20}\text{Ne}/^{22}\text{Ne}$ ratios of 9.27 and 12.45, respectively, and
25 493 $^{36}\text{Ar}/^{38}\text{Ar}$ of 4.74 and 5.04, respectively (see Table 5). Consequently, the CRE ages for
26 494 EM 195 and Famenin suffer from high uncertainties and should be considered with
27 495 extreme caution. We will therefore refer in the following discussion as “nominal” CRE
28 496 ages when evoking the CRE ages of EM 195 and Famenin.

29 497 Regarding lower T_{38} than T_{21} for EM 195 and Famenin, this trend has been already
30 498 reported by Osawa and Nagao (2006). Several reasons can be invoked to explain this
31 499 trend: first, by underestimating the ^{38}Ar production rates. As explained in Graf and Marti
32 500 (1995), for shielding conditions where e.g., contributions of ^{36}Ar are due to radioactive

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3 501 decay of neutron-capture produced ^{36}Cl , the amount of calculated trapped Ar can be
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5 502 overestimated therefore leading to wrong T_{38} ages. Given that the amount of neutron-
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7 503 capture nuclides increase with both size and shielding depth, calculation of CRE ages
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9 504 can be disturbed in the cases of large objects. Finally, one also has to bear in mind that
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11 505 the calculation of CRE ages for solar gas-rich meteorites is likely to be affected by
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13 506 erroneous shielding corrections. However, calculated T_{38} age seems quite consistent in
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15 507 the case of SJ 041. Additionally, one can invoke heterogeneities in the chemical
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17 508 composition within the samples, and in particular in the target elements for the
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19 509 production of ^{38}Ar (e.g., Ca), which could lead to some discrepancies. Note that we only
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21 510 measure samples between $\sim 3 - 5$ mg, which might introduce a bias considering the
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23 511 bulk composition of the meteorite, whereas the equations used for the production rates
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25 512 are for bulk compositions (e.g. Di Gregorio et al. 2019).

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27 513 The nominal CRE ages for Famenin and EM 195 are generally older than the
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29 514 average values reported for H or L chondrites (Graf and Marti 1995; Marti and Graf
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31 515 1992). The CRE age histogram for H chondrites is characterized by major peak
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33 516 centered around 6 - 10 Ma and another cluster identified around 33 Ma (Graf and Marti,
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35 517 1995; Herzog and Caffee, 2014). Older CRE ages (i.e., $T > 40$ Ma) are observed to a
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37 518 lesser extent. Interestingly, the petrologic type H3 (to which Famenin belongs) has CRE
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39 519 age spanning from 5 - 40 Ma, without showing any cluster for CRE ages greater than 40
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41 520 Ma (Herzog and Caffee, 2014). Our nominal CRE age data suggest that both Famenin
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43 521 and EM 195 were ejected at ~ 60 Ma, during an impact event different from those
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45 522 responsible for the ejection of the majority of H and L chondrites (Graf and Marti, 1995;
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47 523 Herzog and Caffee, 2014). However, as mentioned earlier in the discussion, these CRE
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49 524 ages are just nominal, and might suffer from high uncertainties due to huge corrections
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51 525 of the trapped component. A small cluster at ~ 60 Ma is observed (only 7 H chondrite
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53 526 members), except for H3 ordinary chondrites where such a peak is absent (Graf and
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55 527 Marti, 1995). Such old CRE ages would therefore suggest that EM 195 and Famenin
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57 528 may originate from a different parent body, or that both of the meteorites result in a
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59 529 slight deviation from the expected exponential distribution of ordinary chondrites
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61 530 associated with a continuous supply of meteoroids (Graf and Marti, 1995).

531 **Chondrites intermediate between H and L groups**

532 Mineralogical and oxygen isotope evidence indicate that ordinary chondrites
533 originated from multiple parent bodies (Greenwood et al. 2020). In addition to the
534 traditional H-L-LL sequence, accretion of ordinary chondrite parent bodies in conditions
535 more reduced than for H chondrites, and intermediate between the three main groups
536 (H/L and L/LL) have been described (Kallemeyn et al. 1989; Trigo-Rodríguez et al.
537 2009; Wittmann et al. 2011; Pourkhorsandi et al. 2017; Pratesi et al. 2019; Greenwood
538 et al. 2020). This is in agreement with models indicating that the three main OC groups
539 are portions of an incompletely sampled fractionation sequence (e.g., Müller et al.,
540 1971). Based on this evidence, Greenwood et al. (2020) suggest between 3 to 6 parent
541 bodies as the source of ordinary chondrites. Considering the gradual oxygen fugacity
542 changes between different regions in the Solar nebula (e.g., Rubin 1990), the
543 occurrence of meteorites originating from parent bodies with intermediate compositions
544 between H and L chondrites is reasonable (Kallemeyn et al. 1989; Trigo-Rodríguez et
545 al. 2009; Wittmann et al. 2011; Greenwood et al. 2020). Based on their fall date
546 (between May and July), Trigo-Rodríguez et al. (2016) went further and suggested that
547 Bremervörde, Tieschitz, Cali, and Famenin originated from a high-inclination stream of
548 meteoroids formed as a result of disruption of comet C/1919 Q2 Metcalf. However,
549 these meteorites do not have the expected properties of cometary materials (Campins
550 and Swindle 1998; Greenwood et al. 2020).

551 In addition to Famenin, our work on Bremervörde, EM 195, and SJ 041 shows that
552 these meteorites too have intermediate characteristics. One piece of evidence is the
553 magnetic susceptibility values of Tieschitz, Bremervörde, Famenin, EM 195, and SJ 041
554 which are intermediate between mean H and L chondrite values (Rochette et al., 2001).
555 It is also the case for some the samples with available saturation magnetization data
556 (Gattacceca et al., 2014; Dekov et al., 2017). However, for SJ 041 because of its
557 significant terrestrial weathering (W2 grade) this value cannot be interpreted as robustly
558 in terms of original metal content, but it is more in agreement with L chondrite values
559 (Rochette et al. 2012). SJ 041's Fa and Fs values are near the lower limits of L
560 chondrites (Brearley and Jones 1998), but still are outside the limits recommended by

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3 561 the Meteoritical Bulletin Nomenclature Committee for L chondrites (Grossman and
4 562 Rubin, 2011). More importantly, its oxygen isotopic composition, especially $\Delta^{17}\text{O}$ is
5 563 close to the field of Tieschitz, Bremervörde, and Famenin. For weathered meteorites,
6 564 heavier composition (higher $\delta^{18}\text{O}$) can be explained by their high weathering degree
7 565 which is shown to alter oxygen isotopic composition in this manner (Clayton and
8 566 Mayeda 1991) or differences in the metamorphic history or conditions, or even pre-
9 567 metamorphic alteration history (Reimold et al., 2004). As for SJ 041, the weathering
10 568 products (oxides/oxyhydroxides) were removed before the isotopic analysis, the first
11 569 scenario is less likely to be responsible for its relatively heavier composition. Such
12 570 classification complications also is the case for EM 195 which with an intermediate $\log \chi$
13 571 has average olivine and low-Ca pyroxene compositions of $\text{Fa}_{16.9\pm 6.0}$ ($n = 13$) and
14 572 $\text{Fs}_{17.2\pm 5.6}\text{Wo}_{17.2\pm 5.9}$ ($n = 10$), respectively that are in the range of H chondrites values
15 573 (Brearley and Jones 1998). Meanwhile, similar to Famenin its average chondrule size is
16 574 higher than in H chondrites. Oxygen isotopic composition of EM 195 is outside the
17 575 range of equilibrated H and L chondrites. It should be noted that since the Bremervörde
18 576 (H/L3.9), Tieschitz (H/L3.6), EM 195 (H/L3) and Famenin (H/L3.5/3.7) chondrites are
19 577 unequilibrated their oxygen isotope composition is expected to show a larger scatter
20 578 than for equilibrated ordinary chondrites, which prevents robust conclusions to be drawn
21 579 from this dataset. The other interesting case is Gursum that caught our attention
22 580 because of its intermediate $\log \chi$ (5.09) (Rochette et al. 2003) and saturation
23 581 magnetization ($M_s = 28.9 \text{ Am}^2\text{kg}^{-1}$) (Gattacceca et al., 2014). Although based on
24 582 mineral chemistry (Table 2), it is an H chondrite (close to the lower range), our oxygen
25 583 isotope data put it away from the H chondrite field and within the L chondrite field (Fig.
26 584 7). However, it does not plot in the vicinity of H/L field but shows a similar $\Delta^{17}\text{O}$.
27 585 Following these and the fact that Gursum is an equilibrated chondrite whose departing
28 586 oxygen isotope composition cannot be related to heterogeneities found in unequilibrated
29 587 chondrites, we suggest its classification to be updated to an H5-anomalous chondrite.
30 588 Pavel is an anomalous H3 chondrite that has an intermediate $\log \chi$ (5.11) and saturation
31 589 magnetization ($M_s = 26 \text{ Am}^2\text{kg}^{-1}$) in the range of L3 and L4 chondrites falls (Gattacceca
32 590 et al., 2014), but its $\delta^{18}\text{O}$ is higher than H chondrites without a similarity to the
33 591 intermediate chondrites studied here.

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3 592 **Table 8** lists **66** meteorites classified as intermediate chondrites in the Meteoritical
4 Bulletin Database Database as of October 2021. The commonly used H/L designation is
5 593 ambiguous. As described by Kallemeyn et al. (1989), H/L refers to the chondrites with
6 594 bulk chemical properties intermediate between H and L chondrites. However, H/L is
7 595 also often used by classifiers to describe meteorites whose assignment to H or L group
8 596 is unclear, with a meaning close to the H(L) or L(H) classification. While some well-
9 597 described meteorites such as Bremervörde, Cali, LaPaz Icefield (LAP) 031047 and
10 598 Tieschitz are classified as H/L chondrites based on their truly intermediate
11 599 characteristics (Kallemeyn et al. 1989; Trigo-Rodríguez et al. 2009; Wittmann et al.
12 600 2011), the majority of meteorites classified as H/L are simply H or L chondrites that
13 601 have actually not been classified thoroughly for one or several reasons: unequilibrated
14 602 mineral composition and low number of analyzed minerals, no estimate of chondrule
15 603 size, lack of mineral chemistry data, and high weathering grade which decreases the
16 604 efficiency of magnetic classification. Based on the characteristics of truly intermediate
17 605 H/L chondrites (Bremervörde, Cali, EM 195, Famenin, LaPaz Icefield (LAP) 031047, SJ
18 606 041, and Tieschitz), we define ranges for their different characteristics as an attempt to
19 607 identify the “real” intermediate H/L chondrites in the meteorite collection. We define the
20 608 following criteria (**Table 9**): magnetic susceptibility ($\log\chi$) in the 4.95 - 5.20 range, for
21 609 equilibrated ones (type 4 or higher) an average Fa content in the 20 - 24 mol% range,
22 610 average apparent chondrule size in the L chondrites range ($\sim 500 \mu\text{m}$), and $\Delta^{17}\text{O}$
23 611 between 0.8 and 1.2 ‰. After filtering out the poorly classified meteorites, we are left
24 612 with a population of **36** H/L chondrites possibly truly distinct from H and L chondrites
25 613 corresponding to 0.0006% of the total number of classified ordinary chondrites (56417),
26 614 and that would deserve a specific classification nomenclature (**Table 8**). We propose to
27 615 call these latter HL chondrites.
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47 617 Olivine and low-Ca pyroxene data of HL chondrites show that except when they are
48 618 unequilibrated chondrites (such as Famenin and EM 195), their olivine and low-Ca
49 619 pyroxene composition is between H and L chondrite ranges (**Fig. 9**). This phenomenon is
50 620 more evident in olivine Fa content (**Fig. 13**) as it equilibrates faster than low-Ca pyroxene
51 621 during parent body thermal metamorphism (Dodd and Van Schmus, 1967). However, it
52 622 becomes complicated in the case of some HL chondrites such as NWA series 4152-4156
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3 623 (HL6) that have average Fa values of ~ 20, consistent with H chondrites, while average
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5 624 Fs value of ~ 20.4 and out of the range of H chondrites. Other characteristics for HL
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7 625 chondrites, such as oxygen isotopic composition, siderophile content, and metal
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9 626 abundance, suggest that they are indeed distinct chondrites. Considering the fact that
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11 627 meteorites are being classified mostly based on their olivine and low-Ca compositions, it
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13 628 is possible that some unequilibrated HL chondrites have been overlooked and classified
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15 629 either as H3 or L3 chondrites.

15 630 The existence of ordinary chondrites with properties outside of the usual ranges,
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17 631 such as the HL chondrites, can be accounted for by the existence of more than three
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19 632 parent bodies or by compositional heterogeneity of the three main parent bodies. This
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21 633 latter hypothesis would require extending the accepted ranges for the three main
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23 634 groups. Discriminating between the two hypotheses require a more detailed
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25 635 investigation using a larger and a multi-proxy database.

26 636 Hints for the existence of an HL chondrite cluster in the oxygen isotope dataset (Fig.
27
28 637 7) suggest that analyses of more equilibrated HL chondrites should be undertaken to
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30 638 validate the difference in oxygen isotopic composition between these chondrite and H-L-
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32 639 LL sequence. This also applies for noble gas composition measurements and CRE age
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34 640 distribution and comparison with those of the main ordinary chondrite groups. In
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36 641 addition, measurements of bulk rock and (Fe,Ni) metal compositions of the anomalous
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38 642 and intermediate ordinary chondrites would be helpful to unravel their relationship with
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40 643 the three main groups.

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42 43 645 **CONCLUSIONS**

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45 646 Famenin meteorite is a type 3.4/3.8 OC with characteristic distinct from the H and L
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47 647 chondrites. In addition to its primary characteristics (metal content, chondrule size, bulk
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49 648 composition, oxygen isotope composition, olivine and low-Ca pyroxene compositions
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51 649 etc.), Famenin's noble gas composition and CRE age distinguish it from the majority of
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53 650 H and L chondrites. Famenin along with 36 similar OCs might be member of another
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55 651 ordinary chondrite group originating from a different parent body than H, L, and LL
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57 652 chondrites, or originating from regions of these parent bodies that have rarely been

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3 653 sampled. We propose to use a new designation (HL) for these meteorites rather than
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5 654 the ambiguous H/L designation that is also and mostly used for rather poorly
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7 655 characterized meteorites that could be either H or L chondrite. Following previous works
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9 656 on the diversity of ordinary chondrites, this work emphasizes again the existence of
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11 657 more than the three ordinary chondrite groups H, L, and LL, with possibly more than
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13 658 three associated parent bodies. Measuring oxygen isotopic composition of equilibrated
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15 659 HL chondrites, and CRE ages of a larger population of HL chondrites may help to test
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17 660 this hypothesis.
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20 662 **Acknowledgments**

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24 856 **Figure captions:**

25
26 857 **Fig. 1:** Picture showing a) the Famenin fall place on the roof of a house. Note a N-NW
27 fall direction; b-d) Different fragments of the Famenin meteorite. (d) credit: A. Jamshidi.

28 858
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30 859 **Fig. 2:** Optical micrographs of Famenin in transmitted polarized (a) and reflected (b)
31 light.
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34 861 **Fig. 3:** Optical (a & h) and BSE (b-g) images of Famenin. a) Note the fusion crust
35 composed of magnetite, troilite veinlets, and vesicles. g) In this figure, a type I
36 862
37 chondrule, smaller in size with Mg-rich olivine grains and metal droplets can be seen.
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40 864 **Fig. 4:** Size frequency distribution of the chondrule diameters in Famenin, Pavel, and El
41 Médano 195. Horizontal axis values mark the upper limits of the size bins.
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44 866 **Fig. 5:** Composition of randomly chosen a) olivine (n = 71) and b) low-Ca pyroxene (n =
45 867
46 35) grains in Famenin.

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48 868 **Fig. 6:** CI-normalized trace-element chemical composition of Famenin. Mean data for
49 ordinary chondrites are from Wasson and Kallemeyn (1989).
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52 870 **Fig. 7:** $\Delta^{17}\text{O}$ versus $\delta^{18}\text{O}$ values of our analyzed meteorites compared to type 3 (shown
53 in white) and 4-7 (shown in black) H, L, and LL chondrites. Ochansk (H4), Paranaiba
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55 (L6), and Homestead (L5) were analyzed to check the accuracy of the measurement
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3 873 and shown with numbers from 1 to 3, respectively. Ordinary chondrites with
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5 874 compositions intermediate between H and L are shown as HL (see text). The following
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7 875 chondrites that are anomalous and/or have intermediate compositions are shown with
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9 876 the following guide numbers: Pavel (4), Gursum (5), LAP 031047 (6), Bremervörde (7),
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11 877 EM 195 (8), Famenin (9), Bremervörde analyzed during our work (10), Tieschitz (11),
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13 878 and SJ 041 (12). Data sources: LAP 031047 (Wittmann et al. 2011), other samples
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15 879 (Clayton and Mayeda 1991) and the Meteoritical Bulletin Database (Table 2S). $\Delta^{17}\text{O}$
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17 880 values are calculated as $\delta^{17}\text{O} - 0.52 \times \delta^{18}\text{O}$.

18 881 **Fig. 8:** Neon three-isotope diagram for EM 195 and Famenin. Also shown the Ne
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20 882 produced from Galactic Cosmic-Rays (GCR-Ne), Solar Cosmic-Rays (SCR-Ne), Air,
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22 883 and Solar Wind (SW). Errors bars are contained within the symbols and have been
23
24 884 omitted for clarity. Dashed line indicates the mixing line between pure cosmogenic Ne
25
26 885 and SW. Data from Heber et al. (2009).

27 886 **Fig. 9:** Average Fa vs. Fs (%mole) contents of olivine and low-Ca pyroxene of H, L, and
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29 887 LL chondrites, as well as the suggested HL chondrites (Table 8). Ordinary chondrites
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31 888 with compositions intermediate between H and L are shown as HL (more details in text).
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33 889 For H, L, and LL chondrites, only those with petrologic types ≥ 3.9 are shown. Type 3.9-
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35 890 4 H, L and LL chondrites are shown with empty circles while the type 5-7 chondrites are
36
37 891 shown as filled circles. Standard deviation is indicated for type 3 HL chondrites. Data
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39 892 source for H, L, and LL chondrites: Meteoritical Bulletin Database
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41 893 (<https://www.lpi.usra.edu/meteor/>).

42 894 **Fig. 10:** a) Co content in kamacite vs. Fa%. Ordinary chondrites with compositions
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44 895 intermediate between H and L are shown as HL (more details in text). Chondrites and
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46 896 their corresponding numbers are: Djadjarm (1), Andila (2), Taqtaq-e Rasoul (3), Gursum
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48 897 (4), SJ 041 (5), EM 195 (6), Bremervörde (7), and Famenin (8). b) Co vs. Ni contents in
49
50 898 kamacite of Famenin and ordinary chondrites. Chondrites and their corresponding
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52 899 numbers are: Djadjarm (1), Andila (2), Taqtaq-e Rasoul (3), Agen (4), Gursum (5),
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54 900 Tieschitz (6), EM 195 (7), Bremervörde (8), SJ 041 (9), and Famenin (10). Data source
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56 901 (including Bremervörde and Tieschitz): Rubin (1990). Pavel data from Dekov et al.
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58 902 (2017).

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3 903 **Fig. 11:** Chemical composition of Famenin in comparison with ordinary chondrites.
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5 904 Ordinary chondrites with compositions intermediate between H and L are shown as HL
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7 905 (more details in text). Type 3-4 H, L and LL chondrites are shown with empty symbols
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9 906 while the type 5-7 chondrites are shown as filled symbols. Mean composition of H (red),
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11 907 L (blue), and LL (pink) together with individual chondrites are shown for comparison.
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13 908 Bulk rock data are from Wasson and Kallemeyn (1988) and Kallemeyn et al. (1989).
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15 909 Fayalite data are from Rubin (1990).

15 910 **Fig. 12:** Spectral parameters of Raman bands of carbonaceous materials in Famenin and
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17 911 in reference chondrites: $FWHM_D$ vs. I_D/I_G . Averages (points) and standard deviations
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19 912 (bars) are plotted for reference samples (black symbols) and for Famenin (open symbols).
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21 913 Spectral parameters of individual spectrum are plotted for Famenin (small grey
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23 914 diamonds). Reference chondrites data from Bonal et al. (2016).

24 915 **Fig. 13:** Relative frequency (%) distribution of Fa (mole%) contents for in H, L, LL, and
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26 916 HL (Table 8) chondrites. Ordinary chondrites with compositions intermediate between H
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28 917 and L are shown as HL (more details in text). Only ordinary chondrites with petrologic
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30 918 types ≥ 4 are included. Data source: (<https://www.lpi.usra.edu/meteor/>).

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33 920 **Electronic annex:**

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35 921 **Fig. S1:** Famenin fall location.

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38 922 **Fig. S2:** Optical micrograph of El Médano 195 in reflected light.

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40 923 **Fig. S3:** Optical microscopic image of San Juan 041 in reflected light.

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43 924 **Fig. S4:** Optical microscopic image of Pavel in reflected light.

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45 925 **Fig. S5:** Hysteresis properties of Famenin chondrite along with data for fall ordinary
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47 926 chondrites (from Gattacceca et al. 2014). Ordinary chondrites with compositions
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49 927 intermediate between H and L are shown as HL (more details in text).

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51 928 **Fig. S6:** Bulk rock Ga versus fayalite composition of Famenin and ordinary chondrites.
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53 929 Ordinary chondrites with compositions intermediate between H and L are shown as HL
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55 930 (more details in text). Type 3-4 H, L and LL chondrites are shown with empty symbols

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3 931 while the type 5-7 chondrites are shown as filled symbols. Mean composition of H (red),
4 932 L (blue), and LL (pink) together with individual chondrites are shown for comparison.
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6 933 Bulk rock data are from Wasson and Kallemeyn (1988) and Kallemeyn et al. (1989).
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8 934 Fayalite data are from Rubin (1990).
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955 **Tables:**

956 **Table 1 (Pourkhorsandi et al.):** Trace element ($\mu\text{g/g}$) determined by ICP-MS for
 957 Famenin and Allende as reference sample. Allende composition is reported from the
 958 literature for comparison.

Element	Famenin	Allende	Allende ^a	Allende ^b	Allende ^c
Li	1.57	1.58	-	1.5	-
Be	0.025	0.039	-	-	-
Ga	4.9	5.5	6 ± 1	6.15	-
Rb	3.01	1.17	1.2 ± 0.1	1.10	-
Sr	13.1	16.5	12 ± 3	-	-
Y	2.17	2.81	3.1 ± 0.1	3.10	-
Zr	5.8	7.1	9 ± 3	9.0	-
Nb	0.45	0.58	-	0.62	-
Cs	0.164	0.086	-	0.086	-
Ba	2.99	4.8	4 ± 1	4.00	-
La	0.30	0.51	0.52 ± 0.04	0.52	0.53
Ce	0.80	1.30	1.33 ± 0.08	1.33	1.38
Pr	0.12	0.20	0.21 ± 0.01	0.210	0.21
Nd	0.61	1.03	0.99 ± 0.03	0.99	1.07
Sm	0.20	0.32	0.34 ± 0.02	0.34	0.34
Eu	0.080	0.112	0.11 ± 0.01	0.11	0.12
Gd	0.27	0.40	0.42 ± 0.02	0.42	0.44
Tb	0.051	0.072	0.081 ± 0.010	0.081	0.08
Dy	0.34	0.48	0.42 ± 0.03	0.42	0.54
Ho	0.077	0.104	0.10 ± 0.01	0.10	0.11
Er	0.24	0.30	0.29 ± 0.01	0.29	0.31
Tm	0.034	0.054	-	0.0572	0.05
Yb	0.22	0.30	0.30 ± 0.02	0.30	0.33
Lu	0.034	0.046	0.052 ± 0.006	0.052	0.05
Hf	0.16	0.20	0.21 ± 0.01	0.21	-
Ta	0.024	0.040	-	-	-
W	0.11	0.17	-	0.167	-
Pb	0.22	1.27	1.39 ± 0.25		-

U	0.013	0.017	-	0.016	-
Sc	8.2	11.2	11 ± 1	11.0	-
Co	540	605	600 ± 100	612	-
Ni	13073	14800	14200 ± 200	-	-
Cu	74	104	119 ± 19	119	-
Zn	38	110	110 ± 5	117	-

959 The unit is $\mu\text{g/g}$. ^aJarosewich et al. 1987. ^bFriedrich et al. 2003. ^cDauphas and Pourmand 2015.

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961 **Table 2 (Pourkhorsandi et al.):** Representative olivine and low-Ca compositions (in wt%) from Famenin, EM 195, and SJ
 962 041.

	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	Cr ₂ O ₃	MnO	MgO	CaO	Total	Fa (mol%)	Fs (mol%)
Famenin	41.90	0.04	0.03	6.11	0.65	0.43	49.99	0.09	99.25	6.39	-
	41.59	1.55	0.01	12.27	0.11	0.28	44.84	0.13	100.78	13.26	-
	40.79	0.03	0.00	14.40	0.14	0.27	45.45	0.10	101.18	15.05	-
	40.04	b.d.l.	b.d.l.	15.45	0.33	0.31	43.35	0.11	99.53	16.60	-
	39.81	0.03	0.03	15.63	0.17	0.30	43.70	0.13	99.79	16.65	-
	39.31	0.03	b.d.l.	16.69	0.06	0.28	42.91	0.07	99.35	17.85	-
	39.43	0.04	0.01	16.90	0.02	0.59	42.59	0.02	99.60	18.09	-
	39.86	b.d.l.	0.11	17.04	0.03	0.46	42.89	0.03	100.39	18.13	-
	39.95	0.01	0.02	17.06	0.00	0.38	42.78	0.02	100.22	18.20	-
	39.75	b.d.l.	0.01	17.09	0.02	0.45	42.36	0.03	99.71	18.37	-
	39.39	0.00	0.03	17.04	b.d.l.	0.50	42.16	0.01	99.12	18.38	-
	39.75	0.01	0.02	17.21	0.03	0.48	42.54	b.d.l.	100.03	18.40	-
	39.43	0.01	0.03	17.25	0.01	0.51	41.98	0.01	99.23	18.63	-
	39.52	0.02	0.02	17.37	0.00	0.43	42.28	0.04	99.68	18.64	-
	39.18	0.05	0.07	17.28	0.07	0.48	41.86	0.05	99.04	18.70	-
	40.13	0.05	0.02	17.20	0.37	0.42	41.55	0.05	99.79	18.75	-
	39.05	0.04	0.06	17.34	0.24	0.48	41.67	0.01	98.90	18.82	-
	39.36	b.d.l.	0.04	17.62	0.03	0.49	42.13	0.00	99.64	18.90	-
	40.17	0.25	0.04	17.38	0.15	0.47	41.20	0.08	99.74	19.03	-
	39.06	0.00	b.d.l.	18.11	0.00	0.45	41.76	0.01	99.37	19.47	-
	38.16	0.10	0.00	22.53	0.22	0.30	38.17	0.07	99.54	24.79	-
	58.67	0.36	0.07	3.63	1.11	0.58	34.16	1.97	100.56	-	6.27
	58.80	0.11	0.03	4.17	0.31	0.29	36.36	0.26	100.33	-	6.41
	56.77	0.14	0.13	10.88	0.12	0.52	30.99	0.68	100.21	-	16.90
	56.61	0.82	0.11	11.31	0.98	0.29	29.69	0.97	100.77	-	17.71
	55.11	0.05	0.01	17.62	0.59	0.66	25.44	0.29	99.78	-	28.67

	55.96	0.70	0.10	18.38	0.67	0.77	21.60	1.96	100.14	-	32.21
EM 195	38.62	n.d.	b.d.l.	20.62	n.d.	0.46	38.62	b.d.l.	98.31	23.05	-
	38.84	n.d.	b.d.l.	18.27	n.d.	0.39	40.41	b.d.l.	97.90	20.23	-
	39.02	n.d.	b.d.l.	17.02	n.d.	0.42	41.60	b.d.l.	98.06	18.67	-
	40.81	n.d.	b.d.l.	11.40	n.d.	0.03	46.60	b.d.l.	98.84	12.07	-
	40.07	n.d.	b.d.l.	17.48	n.d.	0.53	41.10	b.d.l.	99.18	19.27	-
	40.15	n.d.	b.d.l.	17.37	n.d.	0.45	40.87	b.d.l.	98.84	19.26	-
	40.39	n.d.	b.d.l.	15.40	n.d.	0.50	41.72	b.d.l.	98.01	17.16	-
	55.29	n.d.	0.23	11.26	n.d.	0.50	30.12	0.48	97.87	-	17.17
	56.65	n.d.	0.20	10.46	n.d.	0.50	30.55	0.39	98.75	-	15.99
	58.06	n.d.	b.d.l.	6.64	n.d.	0.34	33.35	0.16	98.54	-	10.02
	57.00	n.d.	0.19	10.91	n.d.	0.56	30.48	0.42	99.56	-	16.59
	53.83	n.d.	b.d.l.	18.47	n.d.	0.57	24.64	0.61	98.12	-	29.24
	57.89	n.d.	b.d.l.	5.69	n.d.	0.37	34.28	0.17	98.39	-	8.49
	55.42	n.d.	b.d.l.	14.75	n.d.	0.48	26.52	0.62	97.80	-	23.48
	57.28	n.d.	b.d.l.	10.63	n.d.	0.56	29.96	0.80	99.23	-	16.34
SJ 041	38.73	n.d.	n.d.	20.46	b.d.l.	0.47	39.97	0.00	99.62	22.31	-
	38.69	n.d.	n.d.	20.42	b.d.l.	0.51	40.00	0.00	99.62	22.27	-
	39.65	n.d.	n.d.	20.84	b.d.l.	0.43	40.16	0.00	101.08	22.55	-
	38.45	n.d.	n.d.	20.88	b.d.l.	0.49	39.81	0.00	99.63	22.74	-
	55.59	n.d.	n.d.	12.35	0.62	0.47	30.55	0.26	99.84	-	18.39
	55.57	n.d.	n.d.	12.03	0.37	0.46	30.57	0.63	99.62	-	17.88
	55.66	n.d.	n.d.	12.81	0.21	0.47	30.13	0.30	99.58	-	19.15
	56.53	n.d.	n.d.	11.48	0.36	0.45	30.88	0.34	100.04	-	17.15
	55.60	n.d.	n.d.	12.57	0.59	0.27	29.00	1.39	99.41	-	19.03
Gursum	37.36	n.d.	n.d.	14.61	0.03	0.54	44.50	0.00	97.12	15.55	-
	38.51	0.02	n.d.	15.19	n.d.	0.52	43.78	0.02	98.08	16.30	-
	38.62	0.01	0.02	14.86	0.02	0.53	44.35	0.00	98.46	15.83	-
	38.57	n.d.	n.d.	14.74	0.06	0.51	43.87	0.00	97.81	15.86	-
	38.05	0.01	0.02	15.33	n.d.	0.47	43.97	0.02	97.98	16.36	-

	55.19	0.19	0.26	9.67	0.21	0.60	31.46	0.76	98.38	-	14.50
	54.83	0.18	0.24	9.56	0.17	0.52	32.13	0.63	98.28	-	14.14
	53.86	0.17	0.22	9.73	0.15	0.66	32.14	0.74	97.76	-	14.31
	53.56	0.09	0.11	9.25	0.12	0.58	32.02	0.72	96.49	-	13.75
	55.35	0.18	0.12	9.59	0.08	0.61	32.04	0.68	98.65	-	14.20
	54.23	0.17	0.22	9.69	0.11	0.53	32.42	0.66	98.11	-	14.19

963 Detection limits (wt%) = Si (0.07), Al (0.06), Ti (0.13), Fe (0.16), Cr (0.07), Mn (0.14), Mg (0.07), Ca (0.05). b.d.l. = below detection limit. n. d. = not determined.

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966 **Table 3 (Pourkhorsandi et al.):** (Fe,Ni) metal compositions (in wt%) in Famenin, EM 195, Gursum, and SJ 041.

Meteorite	Fe	Co	Ni	Total	Meteorite	Fe	Co	Ni	Total
Famenin	96.79	0.58	3.22	100.58	EM 195	93.71	0.30	6.65	100.66
	95.52	0.70	4.64	100.87		93.37	0.36	6.69	100.43
	94.99	0.75	5.21	100.95		93.32	0.20	6.67	100.48
	94.88	0.34	5.42	100.65		93.30	0.29	7.11	100.70
	94.48	0.34	6.64	101.4		92.65	0.28	6.72	99.65
	94.36	0.49	6.07	100.92		92.57	0.32	7.18	100.07
	93.86	0.56	6.70	101.11		92.36	0.34	7.09	99.78
	93.36	0.30	6.65	100.31		91.55	0.28	6.85	98.68
	93.16	0.48	6.40	100.04	Gursum	93.97	0.30	6.50	100.76
	93.16	0.25	6.89	100.29		93.24	0.15	6.41	99.80
	92.81	0.34	6.74	99.89		93.23	0.29	6.28	99.80
	92.63	0.30	6.85	99.78		93.00	0.23	6.31	99.53
	92.19	0.29	6.72	99.21		92.23	0.29	6.24	98.76
	91.90	0.59	6.11	98.60		91.84	0.41	6.73	98.98
75.40	0.19	25.27	100.86	91.71	0.17	6.42	98.30		
72.80	0.22	27.81	100.82	91.68	0.21	6.26	98.15		

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72.38	b.d.l.	27.97	100.36	SJ 041	72.96	b.d.l.	26.83	99.79
68.52	b.d.l.	32.87	101.39		72.77	b.d.l.	27.42	100.19
67.93	b.d.l.	32.47	100.40		72.28	b.d.l.	27.23	99.51
67.83	b.d.l.	32.48	100.31		94.58	0.42	6.22	101.23
67.73	b.d.l.	31.73	99.46		94.00	0.50	6.25	100.75
66.99	b.d.l.	33.28	100.27		93.23	0.43	5.34	99.00
66.13	b.d.l.	33.43	99.69		92.35	0.52	7.07	99.95
65.98	b.d.l.	33.85	99.56		92.32	0.57	6.81	99.70
65.01	b.d.l.	34.10	99.11		92.15	0.57	6.86	99.57
64.00	b.d.l.	35.37	99.37		92.06	0.53	6.75	99.35
52.52	b.d.l.	48.10	100.62		91.81	0.43	6.95	99.19
48.69	b.d.l.	50.95	99.64		91.37	0.43	6.71	98.51
					58.47	b.d.l.	40.42	98.89

967 b.d.l. = below detection limit. Detection limits (wt%) = Fe (0.21), Co (0.18), Ni (0.18).

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969 **Table 4 (Pourkhorsandi et al.):** Results of the whole rock oxygen isotopes analyses.

Meteorite	Group	$\delta^{18}\text{O}$ (‰)	$\delta^{17}\text{O}$ (‰)	$\Delta^{17}\text{O}$ (‰)	Bulk sample mass (mg)
Bremervörde	H/L3	5.53	3.84	0.96	27
El Médano 195	H/L3	5.01	3.41	0.81	
Famenin	H/L3	5.73	3.98	1.00	51
	H/L3	5.17	3.65	0.97	51
Gursum	H5-an	4.28	3.35	1.12	
Pavel	H3-an	5.05	3.26	0.63	27
Ochansk	H4	4.33	2.97	0.72	59
Homestead	L5	5.41	3.87	1.06	119
Paranaiba	L6	4.99	3.71	1.11	80
San Juan 041	H/L6	5.99	4.14	1.02	

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971 **Table 5 (Pourkhorsandi et al.):** Measured He, Ne, and Ar concentrations and isotopic ratios in the studied meteorites.

Meteorite	Mass (mg)	^3He ($10^{-8}\text{cm}^3\text{STP/g}$)	$^3\text{He}/^4\text{He}$ ($\times 10^{-4}$)	^{20}Ne ($10^{-8}\text{cm}^3\text{STP/g}$)	$^{20}\text{Ne}/^{22}\text{Ne}$	$^{21}\text{Ne}/^{22}\text{Ne}$	^{38}Ar ($10^{-8}\text{cm}^3\text{STP/g}$)	$^{36}\text{Ar}/^{38}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$
SJ 041	5.43	8.02±0.30	0.095±0.004	1.16±0.13	0.82±0.02	0.89±0.02	0.63±0.06	3.96±0.57	250±36
EM 195	3.06	0.28±0.03	6.65±0.13	60.2±6.9	9.27±0.02	0.19±0.01	2.62±0.27	4.74±0.69	535±78
Famenin	3.60	0.98±0.08	3.27±0.04	80.1±9.1	12.45±0.02	0.097±0.005	2.46 ±0.25	5.04±0.73	90±13

972 The given uncertainties (1σ) include the uncertainties for the ion current measurements and uncertainties caused by the corrections for interfering isotopes and
 973 corrections for instrumental mass fractionation. Systematic uncertainties in the calibration standard are included; they amount to about 4% for concentrations and
 974 1% for isotope ratios.

976 **Table 6 (Pourkhorsandi et al.):** Cosmogenic He, Ne, and Ar concentrations and isotopic ratios in the studied meteorites.

Meteorite	Mass (mg)	$^3\text{He}_{\text{cos}}$ ($10^{-8}\text{cm}^3\text{STP/g}$)	$^3\text{He}/^4\text{He}$ ($\times 10^{-4}$)	$^{21}\text{Ne}_{\text{cos}}$ ($10^{-8}\text{cm}^3\text{STP/g}$)	$(^{22}\text{Ne}/^{21}\text{Ne})_{\text{cos}}$	$^{36}\text{Ar}_{\text{cos}}$ ($10^{-8}\text{cm}^3\text{STP/g}$)	$^{38}\text{Ar}_{\text{cos}}$
San Juan 041	5.43	8.02±0.30	0.095±0.004	1.76±0.20	1.12±0.06	0.232±0.026	0.368±0.042
El Médano195	3.06	0.28±0.03	6.65±0.13	1.13±0.13	1.95±0.10	0.116±0.013	0.184±0.021
Famenin	3.60	0.98±0.08	3.27±0.04	0.52±0.06	2.52±0.13	0.205±0.023	0.325±0.037

977 The given uncertainties (1σ) include the uncertainties for the ion current measurements and uncertainties caused by the corrections for interfering isotopes and
 978 corrections for instrumental mass fractionation. Systematic uncertainties in the calibration standard are included; they amount to about 4% for concentrations and
 979 1% for isotope ratios.

980 *Assuming ^3He to be entirely cosmogenic.

982 **Table 7 (Pourkhorsandi et al.):** Production rates P_3 , P_{21} , and P_{38} ($10^{-8}\text{cm}^3\text{STP/g/Ma}$) and cosmic-ray exposure ages T_3 ,
 983 T_{21} , and T_{38} (Ma).

Meteorite	Mass (mg)	P_3	T_3	P_{21}	T_{21}	P_{38}	T_{38}
SJ 041	5.43	1.61±0.06	4.99±0.60	0.332±0.004	5.30±0.6	0.042±0.005	8.71±0.99

EM 195	3.06	--	--	0.019±0.002	59.2±9.6	0.010±0.001	17.7±2.0
Famenin	3.60	--	--	0.0078±0.0009	66.4±7.6	0.0069±0.0008	47.4±5.4

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985 **Table 8 (Pourkhorsandi et al.):** A list of meteorites classified with intermediate characteristics between H and L
 986 chondrites reported in the Meteoritical Bulletin and suggested HL chondrites.

Name	Class	Weathering grade	Fa (mol%)	Fs (mol%)	Magnetic Susceptibility	Saturation Magnetization (Am ² /kg)	Comments
Bremervörde [*]	H/L3.9	W0	18.6	-	4.97	15.12	-
Calama 085 [*]	H(L)3	W3	20.3 ± 7.8	20.0±2.6	-	-	-
Cali [*]	H/L4	W0	22.8 ± 0.9	15.8 ± 6.9	5.11	-	-
Chug Chug 022 [*]	L(H)3	W1	22.7 ± 8.28	14.5 ± 7.61	-	-	-
DaG ^a 369	L(H)3	W3	16.8 (9.3-27.4)	9.1 (4.4-17.7)	-	-	-
DaG 378	H(L)3	W2	14.3 (0.9-26.6)	7.9 (2.1-25.2)	-	-	-
DaG 591	H(L)6	W3	20	17.4	-	-	Highly weathered
Dhofar 428 [*]	H/L5	W4	21.5	18.5	-	-	-
Dhofar 1022	H(L)3-an	W4	18.5 ± 1.3	16.5 ± 5.5	-	-	-
Dhofar 1035	H(L)3	W4	21 ± 4	15.5 ± 3.5	-	-	Highly weathered
Dhofar 2058	H(L)6	W4	-	-	4.67	-	Needs average Fa data
EM ^b 195 [*]	H/L3	W1	16.9 ± 6.0	17.2 ± 5.6	4.99	-	-
Famenin [*]	H/L3	W0	17.4 ± 3.7	17.1 ± 9.0	5.09	24.9	-
Gursum	H5-an	W0	16.0 ± 0.3	14.2 ± 0.2	5.09	28.88	-
Haxtun [*]	H/L4	W4	21.6 ± 0.4	17.8 ± 1.3	-	-	-
JaH ^c 113	H/L4	W2	-	-	4.9	-	Needs average Fa data

1	JaH 805	L(H)3	W3	12.6 – 34.2	7.7 – 15.7	4.8	-	Highly weathered
2	Königsbrück*	H/L4	W1	22.6	8.2 – 20.1	-	-	-
3	LAP ^d 031047*	H/L	A	23	17	-	-	Needs more work
4	NWA ^e 1518*	H/L3	W2	21	18.3	-	-	-
5	NWA 1534*	H/L4	W2	20.5	17.6	-	-	-
6	NWA 1554	L/H4	W3	-	-	5	-	Needs average Fa data
7	NWA 1955	H/L3-4	-	20.6	20.44	-	-	-
8	NWA 1976	L(H)3	W3	14.5 ± 8	11 ± 8	-	-	-
9	NWA 2001*	H/L4	W0	22	19.3	5.21	-	-
10	NWA 2521	H/L3	W2	18.2 ± 7.3	14.3 ± 6.1	-	-	Needs average Fa data
11	NWA 2617	H/L4	W2	19.5 - 20.5	16.2 - 21.2	4.93	-	Needs average Fa data
12	NWA 3330*	H/L5	W3	21.8	18.8	-	-	-
13	NWA 3342	H/L4	W1	17 - 28	11.2 - 19.9	-	-	Needs average Fa data
14	NWA 4089*	H/L4/5	W3	21.2	18.1	-	-	-
15	NWA 4097	H/L3	W2	7.9 - 24	4.7 - 18.8	-	-	Needs average Fa data
16	NWA 4150	H/L6 Imc	W0/1	24.1	19.9	-	-	-
17	NWA 4152*	H/L6	W2	20.4	20.4	-	-	-
18	NWA 4153*	H/L6	W3	20.1	20.1	-	-	-
19	NWA 4154*	H/L6	W4	20.6	20.6	-	-	-
20	NWA 4155*	H/L6	W3	21.2	21.2	-	-	-
21	NWA 4156*	H/L6	W3	19.9	19.9	-	-	-

NWA 4334	H/L3	W1	2.0 - 30.0	4.3 - 17.2	-	-	Needs average Fa data
NWA 4357	H/L3	W1	3.7 - 31.1	2 - 24.3	-	-	Needs average Fa data
NWA 4725	H/L3	W2	16.3 ± 9.1	5.17 ± 3.09	-	-	Needs average Fa data
NWA 4726	L/H5	W2	24.67 ± 0.31	22.06 ± 1.33	4.98	-	Needs average Fa data
NWA 5809*	H/L5	W3	20.7	17.5 - 18.2	4.95	-	-
NWA 5945*	H/L3	-	24.2 ± 2.0	14.5 ± 5.7	-	-	-
NWA 7327*	H/L5	W3	20.5 ± 0.3	18.4 ± 1.5	-	-	-
NWA 8123	H(L)3.1	W2/3	0.3 – 97.1	2.0 – 12.7	4.02	-	Needs average Fa data, low logx
NWA 8793	H(L)3	W2/3	11.3 – 30.6	4.5 – 15.2	4.68	-	Needs average Fa data
NWA 10287*	H/L5	W0/1	21.7 - 21.9	18.4 - 19.1	5.2	-	-
NWA 11570*	H/L4	W5	21.7 ± 1.0	17.6 ± 6.6	-	-	-
NWA 13520	L(H)3	W2	16.9 ± 6.4	9.4 ± 5.4	-	-	Needs magnetic data
Pavel	H3-an	W0	19.7 ± 1.9	19.0 ± 6.3	5.11	26	-
SJ ^f 041*	H/L6	W2	22.5 ± 0.2	18.3 ± 0.8	4.59	-	-
SaU ^g 147	H/L4	W3	19.5	17.2	-	-	-
SaU 185	L/H4-5	W2	19.4 - 24.5	17.2 - 20.6	-	-	-
SaU 301	H/L4	W1	19.0 - 20.0	16.6 - 19.2	4.99	-	-
SaU 324	H/L6	W3/4	20.3	17.6	-	-	-
Sierra Gorda 028*	H/L5	W1	21.8 ± 0.24	18.4 ± 0.32	-	-	-
Tieschitz*	H/L3.6	W0	-	-	4.98	16.79	-
Y ^h -74645*	H/L4	-	21.1	17.9	-	-	-

Y-9405	H/L4	-	-	-	-	-	Needs more data
Y-983336*	H/L5	B	21	19.2	-	-	-
Y-983388*	H/L6	C	21.1	18.3	-	-	-
Y-983430*	H/L5	A/B	20.9	18.4	-	-	-
Y-983551*	H/L6	C	21.5	18.5	-	-	-
Y-983629*	H/L6	A/B	20.9	18.5	-	-	-
Y-983931*	H/L4	A/B	21.3	13.2	-	-	-
Y-000746	H/L4-5	B/C	20.3	14.6	-	-	-
Y-000782*	H/L4	B/C	21	18.5	-	-	-

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988 ^aDar al Gani, ^bEl Médano, ^cJiddat al Harasis, ^dLaPaz Icefield, ^e Northwest Africa, ^fSan Juan, ^gSayh al Uhaymir, ^h Yamato.

989 Data source: Meteoritical Bulletin. Mineral chemistry, magnetic susceptibility, and saturation magnetization data for Bremervörde are from Rubin (1990), Rochette
 990 et al. (2003), and Gattacceca et al. (2014), respectively. Same data for Cali and Pavel are from Trigo-Rodríguez et al. (2009) and Dekov et al. (2017),
 991 respectively. Magnetic susceptibility and saturation magnetization data of Tieschitz and Gursum from Rochette et al. (2003) and Gattacceca et al. (2014),
 992 respectively.

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994 **Table 9 (Pourkhorsandi et al.):** Suggested criteria for classifying HL chondrites.

Criteria	Suggested values
Magnetic susceptibility (log χ)	4.95-5.20
Average chondrule size (μm)	~ 500
Fa content (mol%)	20-24
$\Delta^{17}\text{O}$ (‰)	0.8-1.2

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998 **Table 1S (Pourkhorsandi et al.):** (Fe,Ni) metal compositions (in wt%) of Catalina 396, Taqtaq-e Rasoul, Agen, Andila,
 999 Djadjarm, Ausson, and Bensour.

Meteorite	Fe (wt%)	Ni (wt%)	Co (wt%)	Total
Catalina 396 (H6)	94.44	6.86	0.43	101.73
Catalina 396 (H6)	95.16	7.09	0.52	102.76
Taqtaq-e Rasoul (H5)	66.65	34.97	b.d.l.	101.52
Taqtaq-e Rasoul (H5)	67.68	32.84	0.15	100.67
Taqtaq-e Rasoul (H5)	68.03	32.30	0.14	100.55
Taqtaq-e Rasoul (H5)	93.85	6.46	0.35	100.76
Taqtaq-e Rasoul (H5)	93.92	6.68	0.42	100.99
Taqtaq-e Rasoul (H5)	94.09	6.42	0.35	100.85
Taqtaq-e Rasoul (H5)	94.34	6.48	0.31	101.16
Taqtaq-e Rasoul (H5)	94.75	6.38	0.59	101.71
Taqtaq-e Rasoul (H5)	94.79	5.76	0.16	100.73
Agen (H5)	50.11	48.43	b.d.l.	98.53
Agen (H5)	92.01	5.97	0.38	98.83
Agen (H5)	93.28	6.29	0.40	100.01
Agen (H5)	93.35	6.09	0.27	99.79
Agen (H5)	93.50	6.19	0.37	100.01
Agen (H5)	93.58	5.71	0.51	99.82
Agen (H5)	93.92	5.71	0.47	100.09
Andila (L6)	44.56	54.19	0.19	98.97
Andila (L6)	60.32	38.40	0.12	98.93
Andila (L6)	72.70	26.61	0.23	99.49
Andila (L6)	74.54	25.58	0.49	100.65

Andila (L6)	92.99	6.17	0.73	99.86
Andila (L6)	93.60	5.98	0.77	100.40
Andila (L6)	93.93	4.82	0.96	99.79
Andila (L6)	93.95	6.47	0.80	101.25
Andila (L6)	94.04	6.61	0.45	101.07
Djadjarm (L6)	46.13	51.74	0.03	97.91
Djadjarm (L6)	58.03	32.06	0.03	90.17
Djadjarm (L6)	61.28	37.08	0.03	98.47
Djadjarm (L6)	94.39	6.72	0.96	102.19
Djadjarm (L6)	94.49	6.32	0.70	101.55
Djadjarm (L6)	95.18	6.10	0.86	102.10
Ausson (L5)	58.92	37.54	0.04	96.54
Ausson (L5)	59.63	38.35	b.d.l.	97.93
Ausson (L5)	65.85	32.33	0.03	98.29
Ausson (L5)	66.47	31.32	0.08	97.89
Ausson (L5)	77.99	18.59	0.73	97.42
Ausson (L5)	78.67	18.55	0.56	97.81
Bensour (LL6)	51.09	45.94	1.74	98.85
Bensour (LL6)	51.59	45.98	1.81	99.29
Bensour (LL6)	62.86	0.03	b.d.l.	97.83
Bensour (LL6)	63.05	b.d.l.	b.d.l.	98.18
Bensour (LL6)	63.38	0.00	0.06	98.57
Bensour (LL6)	63.55	b.d.l.	b.d.l.	98.70

b.d.l. = below detection limit. Detection limits (wt%) = Fe (0.21), Co (0.18), Ni (0.18).

1002 **Table 2S (Pourkhorsandi et al.):** Whole-rock oxygen isotopes composition of ordinary chondrites.

Meteorite	Class	$\delta^{18}\text{O}$	$\delta^{17}\text{O}$	$\Delta^{17}\text{O}$
Dhajala	H3	4.12	2.84	0.70
Sharps	H3	3.95	2.70	0.65
RaSa 430	H3	5.12	3.17	0.51
JaH 567	H3	5.55	3.63	0.74
NWA 1709	H3	4.45	2.84	0.53
NWA 3358	H3	4.67	2.91	0.48
NWA 8061	H3	5.78	3.32	0.32
Bath	H4	4.19	2.89	0.71
Beaver Creek	H4	4.27	2.98	0.76
Kesen	H4	4.51	2.98	0.63
Ochansk	H4	3.85	2.82	0.82
Tysnes Island	H4	4.19	2.88	0.70
Weston	H4	4.08	3.00	0.88
Thuathe	H4/5	4.55	3.12	0.75
Carancas	H4/5	4.43	2.98	0.68
Allegan	H5	3.97	2.68	0.61
Ambapur Nagla	H5	3.94	2.80	0.75
Beardsley	H5	4.20	2.93	0.75
Forest Vale	H5	3.82	2.64	0.65
Glenrothes	H5	4.21	2.69	0.50
Leighton	H5	3.87	2.88	0.87
Mason Gully	H5	4.42	3.04	0.74
Pantar	H5	4.09	2.69	0.56
Richardton	H5	4.08	2.74	0.61
Tamdakht	H5	5.01	3.26	0.65
Cape Girardeau	H6	3.79	2.69	0.72
Charsonville	H6	3.83	2.64	0.65
Dhofar 1559	H6	4.62	3.00	0.59
Guareña	H6	4.10	2.89	0.76
Kernouve	H6	4.15	2.94	0.78
Mount Browne	H6	3.88	2.71	0.69

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	Križevci	H6	3.99	2.76	0.68
	Towada	H6	4.04	2.79	0.69
	Queen's Mercy	H6	4.08	2.84	0.72
	Xingyang	H6	3.89	2.83	0.81
	NWA 2898	H7	4.4	2.90	0.62
	NWA 4226	H7	4.64	3.18	0.77
	NWA 4229	H7	4.40	3.03	0.74
	NWA 7024	H7	4.24	2.83	0.63
	NWA 8400	H7	4.64	2.93	0.52
	NWA 12236	H7	4.50	2.94	0.60
	Bremervörde	H/L3	4.57	3.35	0.97
	Tieschitz	H/L3	5.55	3.83	0.94
	Aba Panu	L3	5.08	3.68	1.04
	Catalina 001	L3	5.15	3.66	0.98
	Dhofar 2056	L3	4.74	4.03	1.57
	Hallingeberg	L3	4.79	3.33	0.84
	Khohar	L3	4.52	3.48	1.13
	Mező-Madaras	L3	4.81	3.45	0.95
	NWA 6744	L3	5.05	3.43	0.80
	NWA 6745	L3	5.26	3.54	0.80
	NWA 6864	L3	5.87	3.84	0.79
	NWA 6925	L3	5.57	4.04	1.14
	NWA 8257	L3	4.64	3.27	0.86
	NWA 8258	L3	5.38	3.66	0.86
	NWA 8276	L3	4.79	3.05	0.57
	NWA 10774	L3	5.39	3.84	1.04
	RdDL 067	L3	5.48	3.77	0.92
	SaU 564	L3	4.83	3.63	1.12
	Hedjaz	L3-6	4.57	3.51	1.13
	Atarra	L4	4.88	3.68	1.14

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Bjurböle	L4	4.90	3.55	1.00
Clarendon (c)	L4	4.88	3.66	1.13
Cynthiana	L4	5.44	3.91	1.08
Kendleton	L4	4.61	3.43	1.03
Saratov	L4	4.74	3.48	1.02
Tennassilm	L4	4.56	3.52	1.15
NWA 10954	L4	4.05	3.11	1.01
NWA 7556	L4-6	5.36	3.87	1.08
Ausson	L5	4.60	3.53	1.14
Barwell	L5	4.63	3.57	1.17
Borkut	L5	4.61	3.46	1.06
Chervettaz	L5	4.64	3.66	1.25
Elenovka	L5	4.56	3.44	1.07
Ergheo	L5	5.00	3.58	0.98
Farmington	L5	4.80	3.63	1.13
Homestead	L5	4.62	3.52	1.12
Knyahinya	L5	4.99	3.64	1.05
Mifflin	L5	4.84	3.65	1.13
NWA 11744	L5	5.14	3.78	1.11
NWA 11745	L5	4.93	3.69	1.13
NWA 12386	L5	4.81	3.55	1.05
NWA 13192	L5	5.23	3.88	1.16
NWA 13193	L5	4.78	3.64	1.16
Park Forest	L5	4.69	3.44	1.00
Qidong	L5	4.95	3.66	1.09
Mocs	L5-6	4.55	3.50	1.13
Renchen	L5-6	4.74	3.63	1.17
Bachmut	L6	4.40	3.45	1.16
Bori	L6	4.62	3.46	1.06
Cabezo de Mayo	L6	5.02	3.65	1.04
Katol	L6	4.91	3.57	1.02
Leighlinbridge	L6	4.44	3.46	1.15
Modoc (1905)	L6	4.65	3.50	1.08

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4	Nan Yang Po	L6	4.40	3.26	0.97
5	NWA 8684	L6	5.15	3.88	1.20
6	NWA 13194	L6	4.98	3.67	1.08
7	NWA 13195	L6	4.85	3.61	1.09
8	NWA 13196	L6	5.20	3.83	1.12
9	Tathlith	L6	4.33	3.40	1.15
10	Tillaberi	L6	4.54	3.33	0.97
11	Viñales	L6	4.54	3.48	1.12
12	Xiujingjin	L6	4.51	3.41	1.06
13	Dhofar 008	L7	5.67	3.81	0.86
14	PAT 91501	L7	4.7	3.7	1.26
15	Bishunpur	LL3	6.00	4.11	0.99
16	Chainpur	LL3	5.72	4.01	1.04
17	Krymka	LL3	5.60	4.09	1.18
18	Manych	LL3	5.37	3.75	0.96
19	Ngawi	LL3	5.40	3.98	1.17
20	NWA 2748	LL3	7.21	4.89	1.14
21	NWA 3260	LL3	5.65	3.57	0.63
22	NWA 4522	LL3	5.55	3.84	0.95
23	NWA 6082	LL3	5.95	3.83	0.74
24	NWA 6742	LL3	6.36	4.24	0.93
25	NWA 6867	LL3	5.66	3.54	0.60
26	NWA 8059	LL3	4.40	2.55	0.26
27	NWA 8124	LL3	5.16	3.00	0.32
28	NWA 8649	LL3	5.01	3.25	0.65
29	NWA 10786	LL3	5.28	3.66	0.91
30	Parnallee	LL3	5.15	3.82	1.14
31	SaU 565	LL3	4.95	3.72	1.15
32	Semarkona	LL3	6.09	4.24	1.07
33	St. Mary's County	LL3	5.66	4.18	1.24
34	Vicência	LL3	5.36	3.77	0.98
35	Albareto	LL4	5.31	3.96	1.20
36	Bo Xian	LL4	5.58	4.06	1.16
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Hamlet	LL4	5.31	4.12	1.36
Savtschenskoje	LL4	5.10	3.94	1.28
Soko Banja	LL4	4.85	3.85	1.33
Witsand Farm	LL4	5.32	4.12	1.35
Guider	LL4-6	4.77	3.67	1.19
NWA 8691	LL4-6	5.67	3.98	1.03
Khanpur	LL5	5.03	4.03	1.41
Olivenza	LL5	4.88	3.66	1.13
Paragould	LL5	5.11	4.05	1.39
Siena	LL5	5.32	4.09	1.32
Appley Bridge	LL6	5.07	3.93	1.29
Bensour	LL6	5.30	4.00	1.24
Dhumsala	LL6	5.09	3.80	1.15
Dongtai	LL6	5.08	3.66	1.02
Ensisheim	LL6	4.80	3.90	1.40
Jelica	LL6	4.76	3.75	1.27
Mangwendi	LL6	4.75	3.91	1.44
NWA 6503	LL6	5.30	3.98	1.23
NWA 7988	LL6	5.03	3.82	1.20
NWA 12575	LL6	5.48	4.03	1.18
St. Mesmin	LL6	5.13	3.80	1.13
Saint-Séverin	LL6	4.76	3.63	1.15
Vavilovka	LL6	4.83	3.72	1.21
NWA 969	LL6/7	5.30	4.00	1.24
JaH 513	LL7	5.73	4.07	1.09
NWA 6426	LL7	4.75	3.71	1.24
NWA 7030	LL7	6.15	4.36	1.16
NWA 10103	LL7	5.19	3.93	1.24
NWA 12534	LL7	5.36	4.02	1.23
NWA 12921	LL7	5.59	4.26	1.35

1003 Data source: Clayton & Mayeda (1991) and Meteoritical Bulletin Database (<https://www.lpi.usra.edu/meteor/>).

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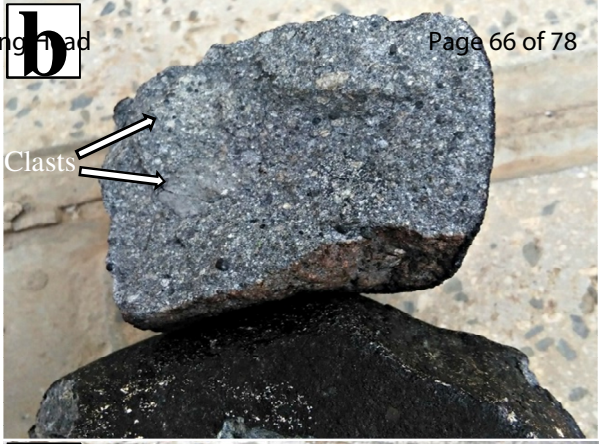
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Running Road
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Clasts



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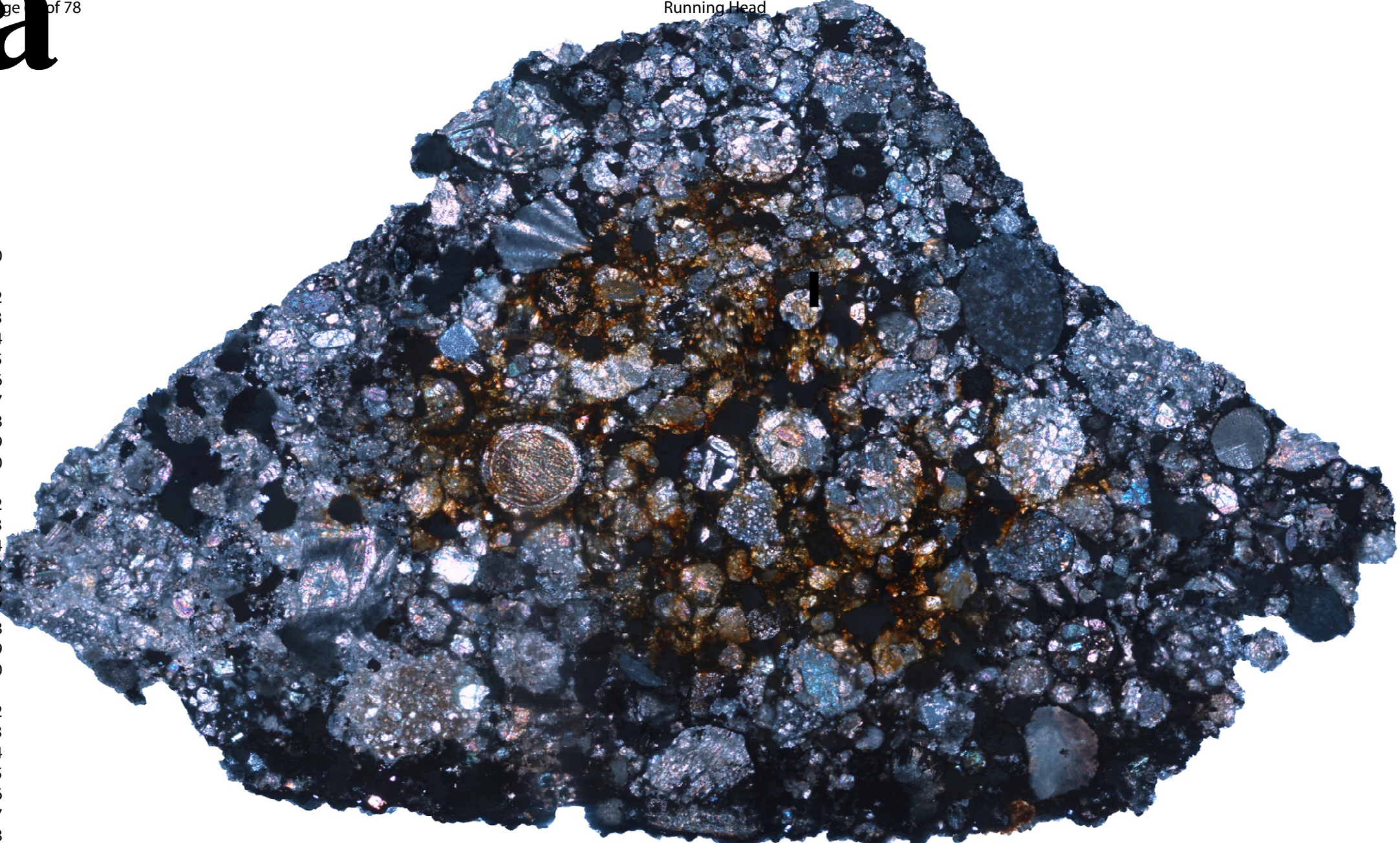
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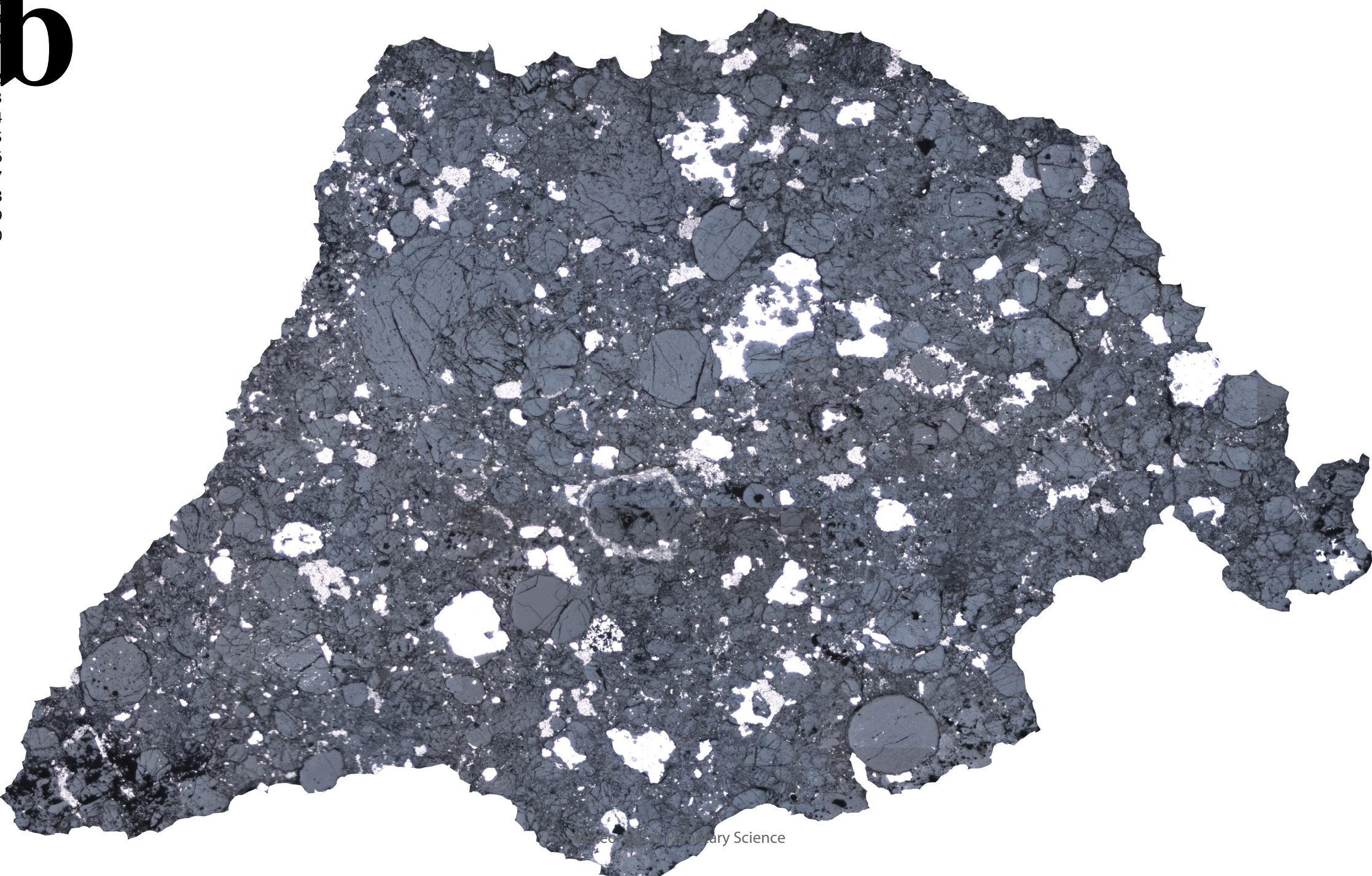
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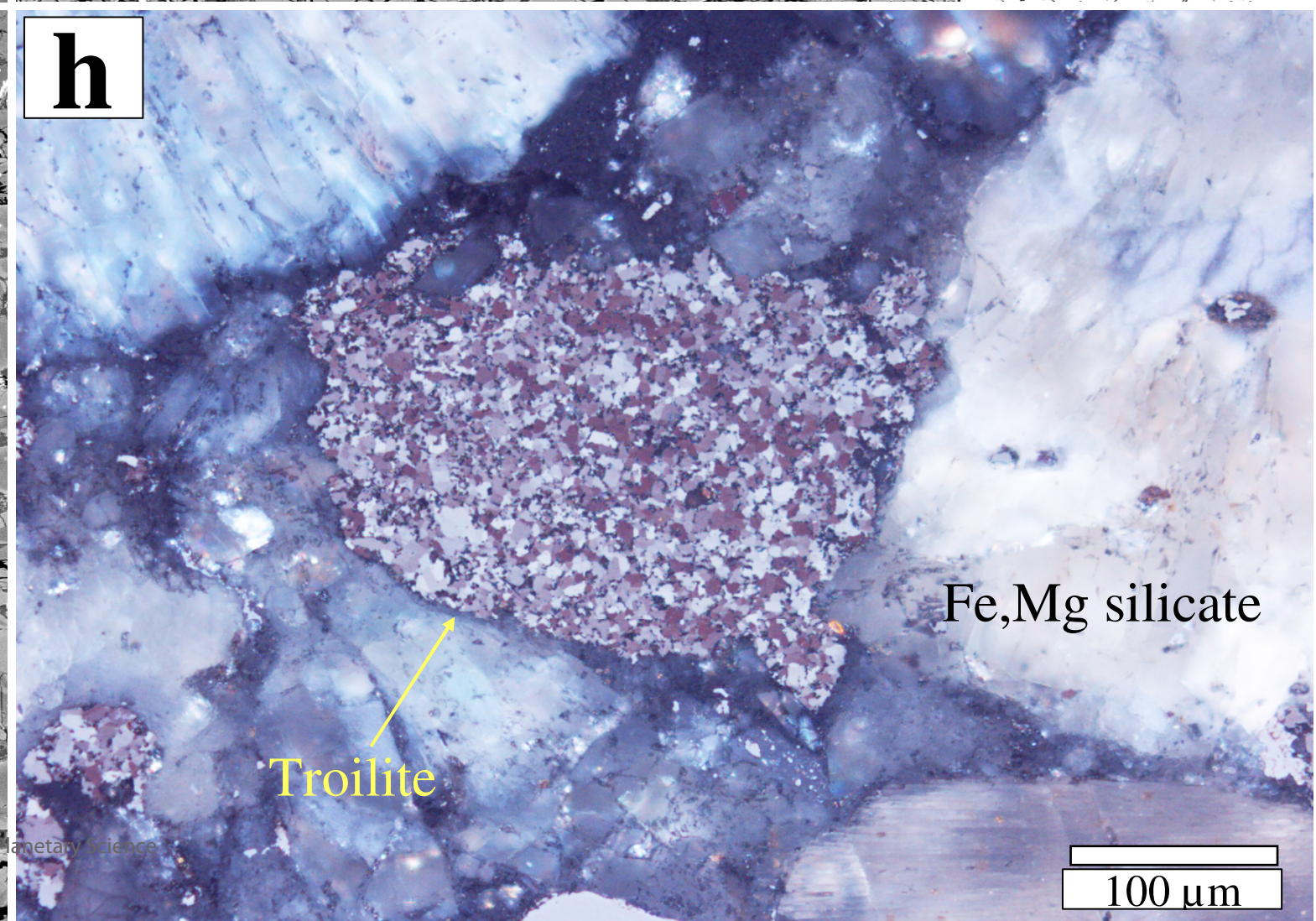
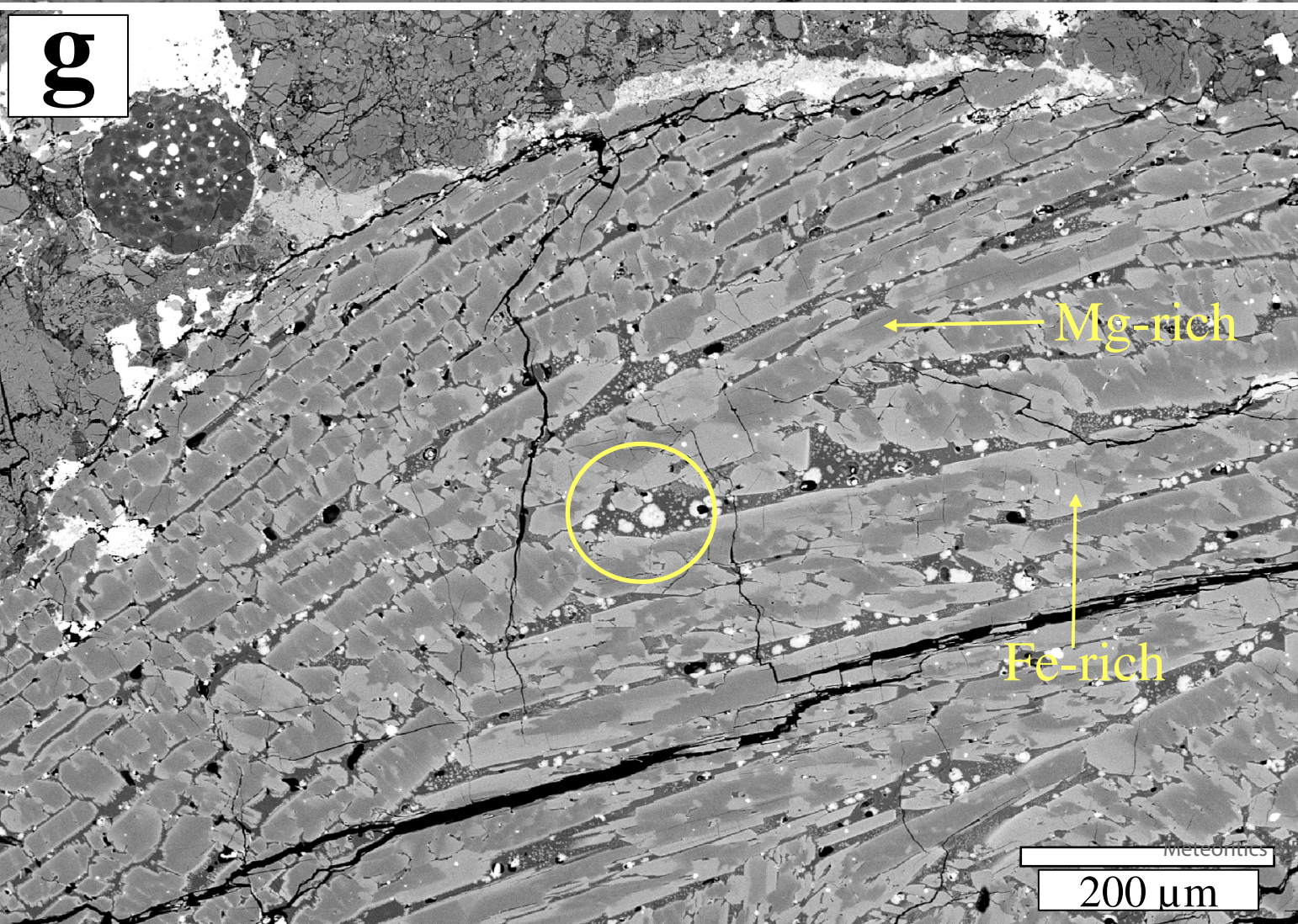
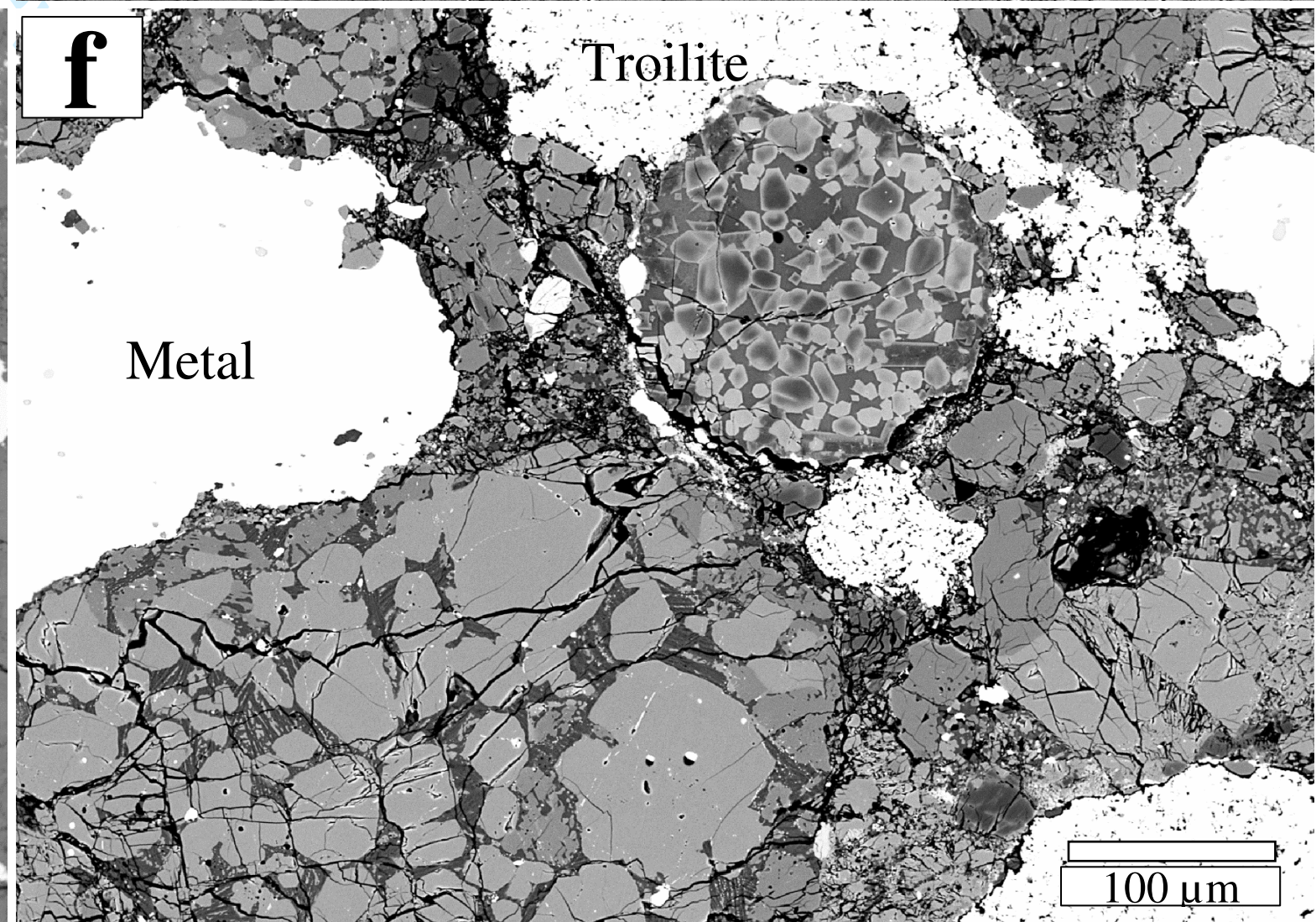
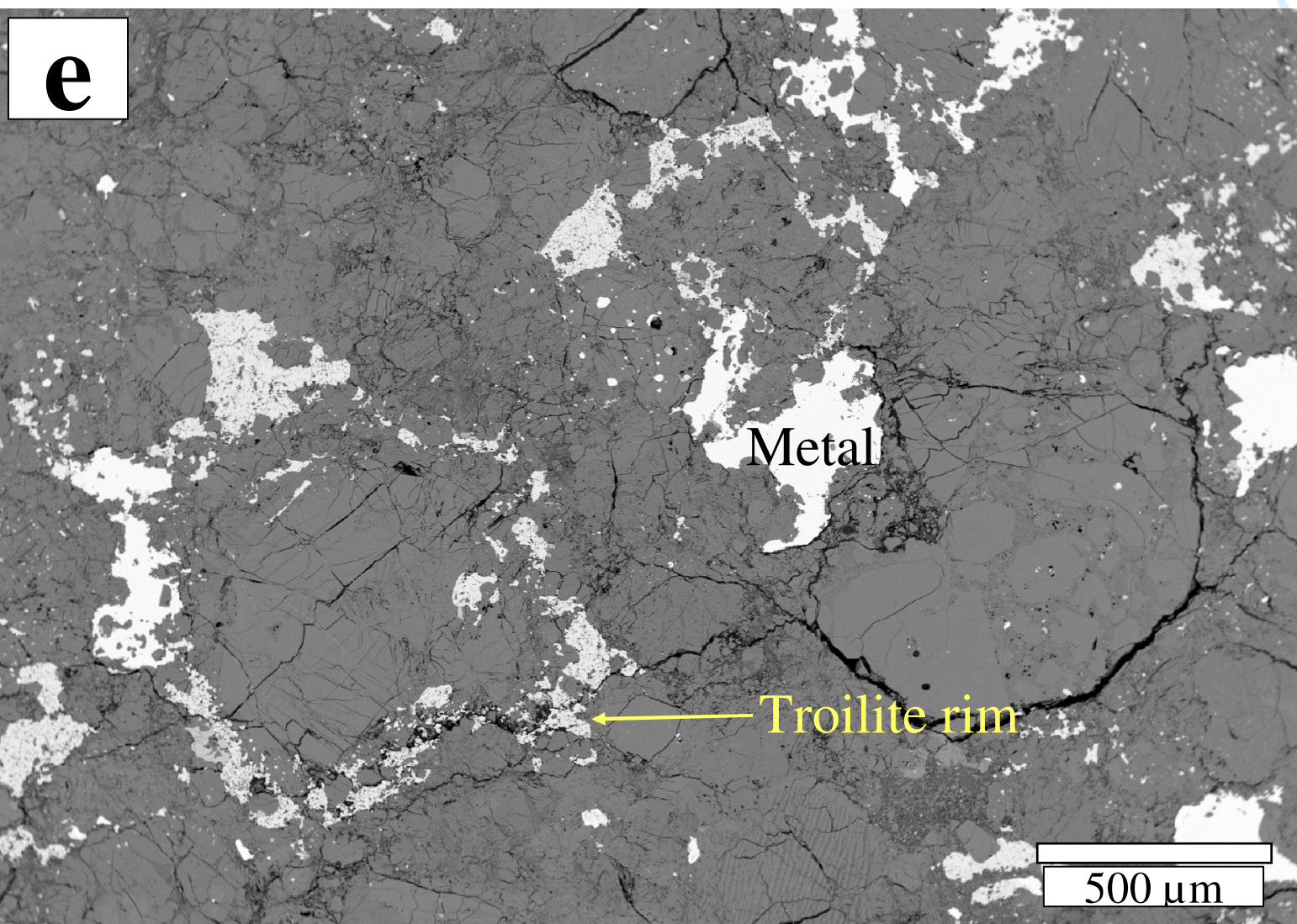
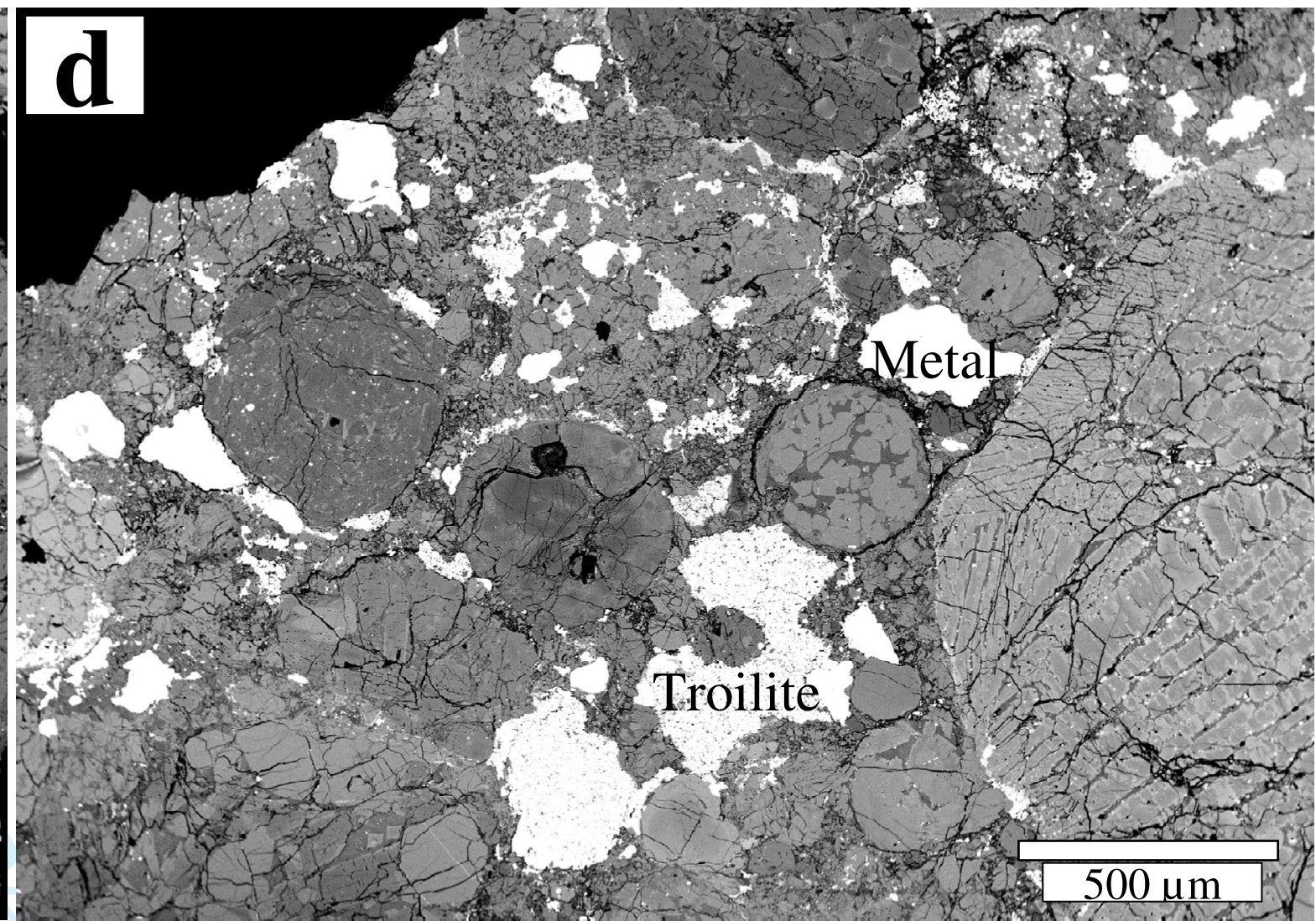
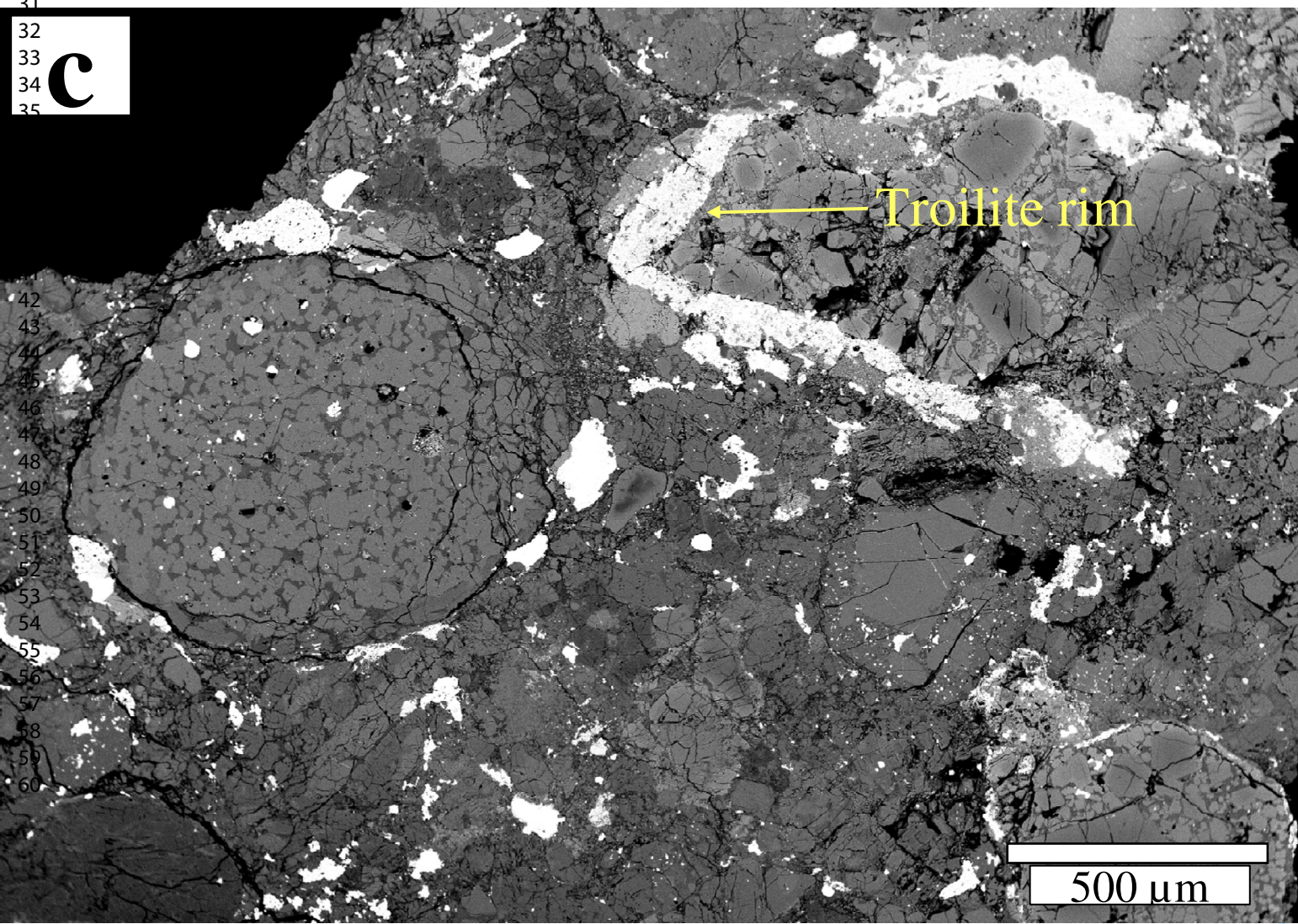
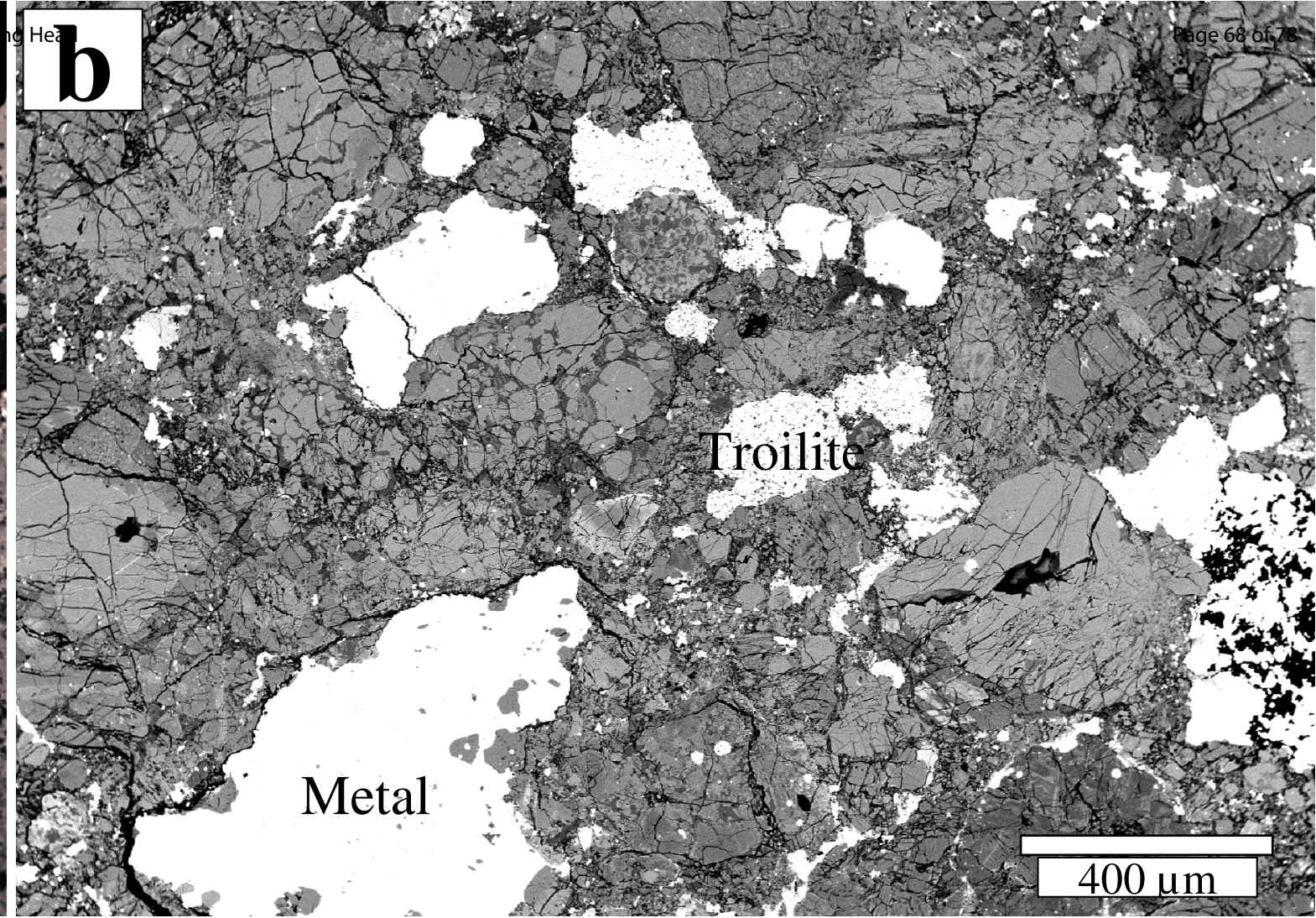
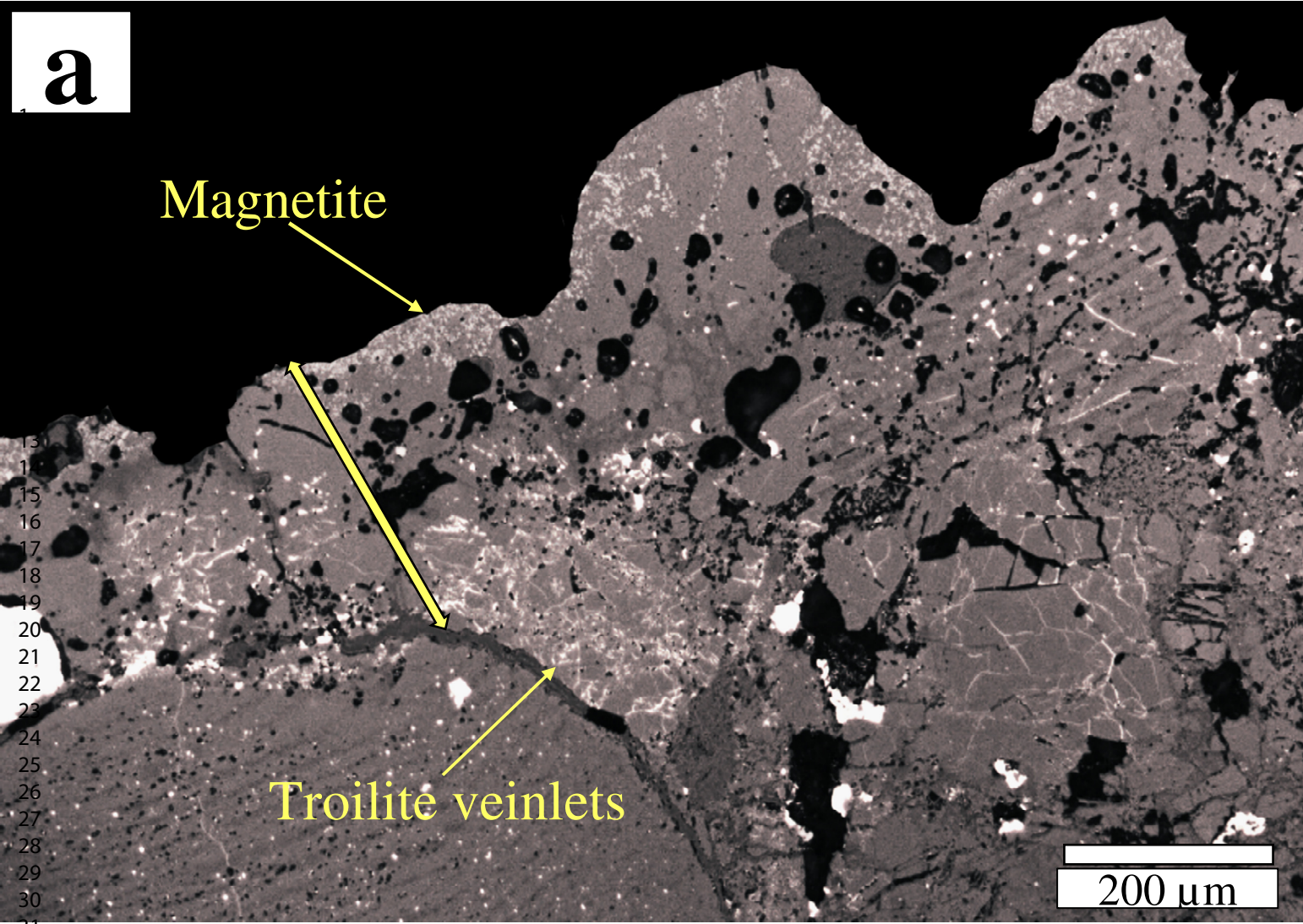


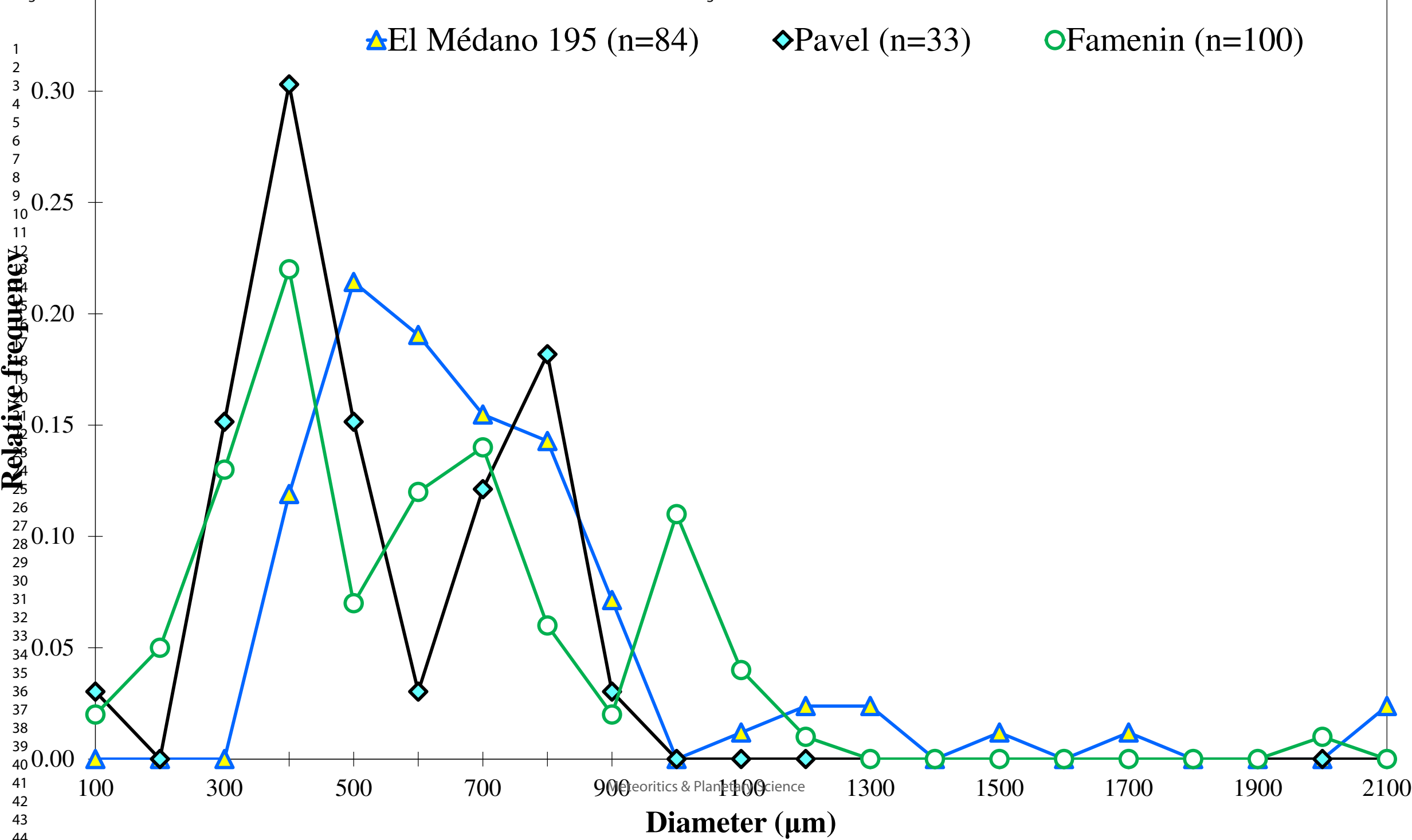
Famenin

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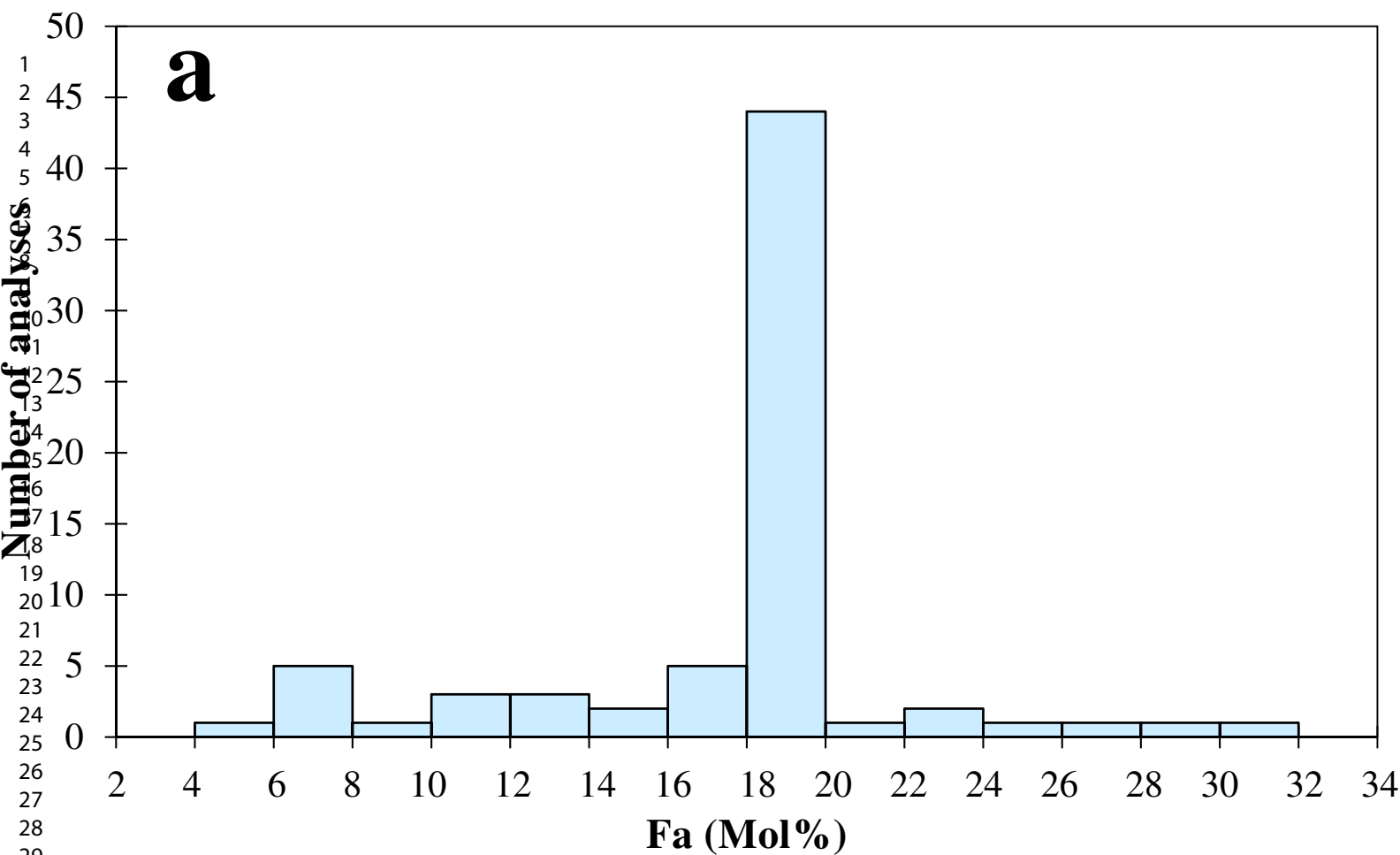
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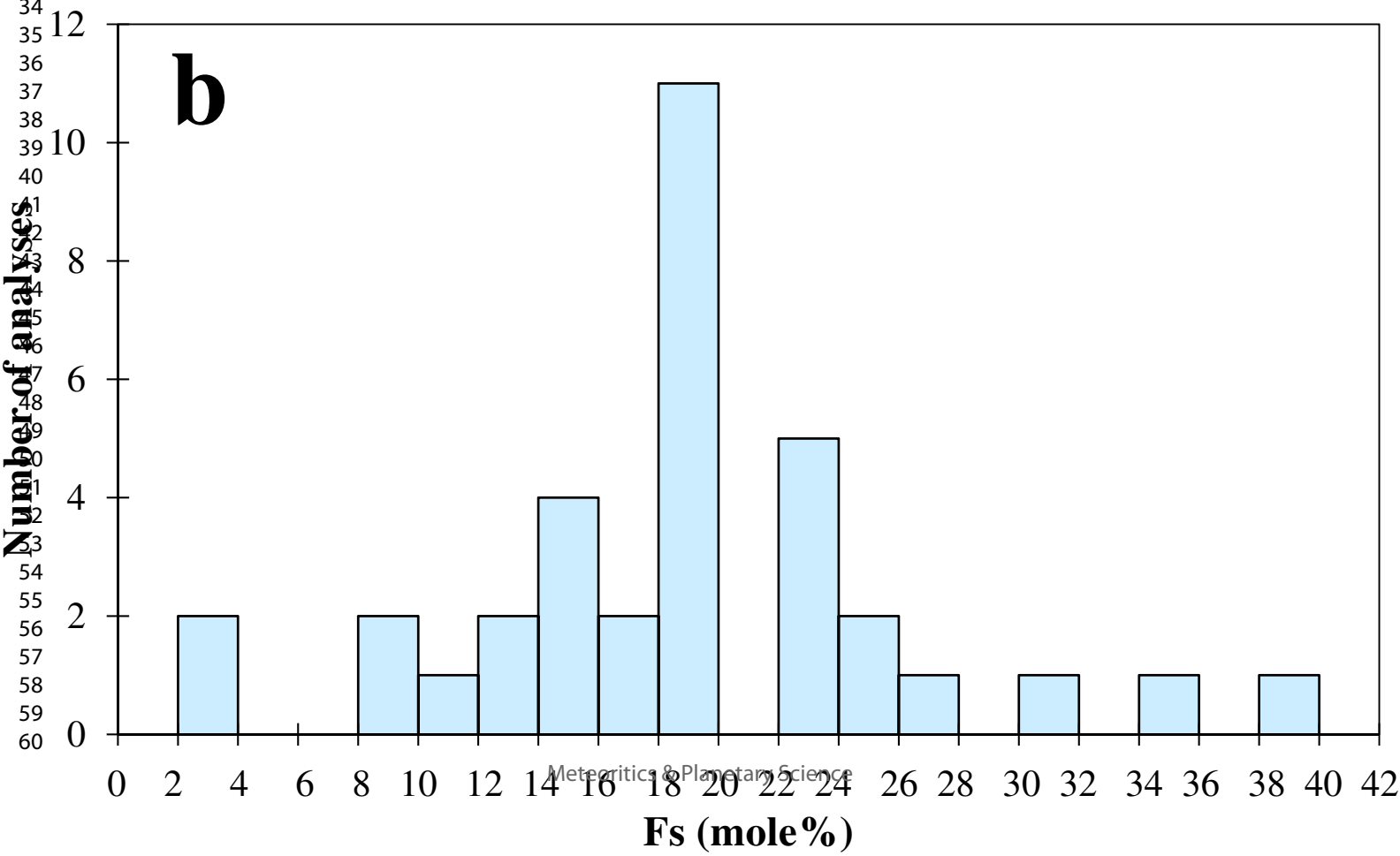




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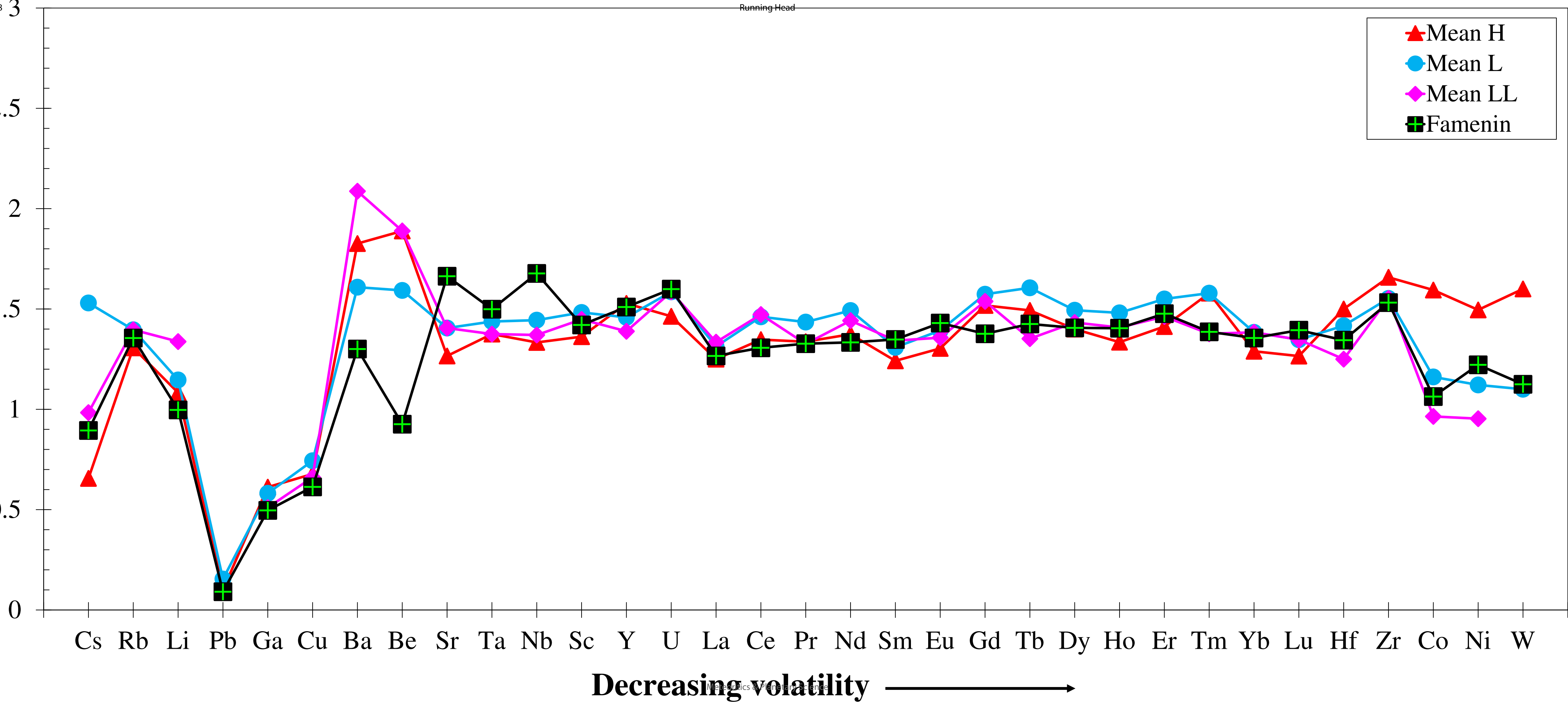
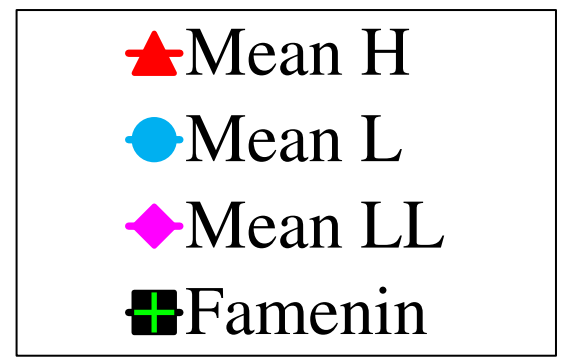


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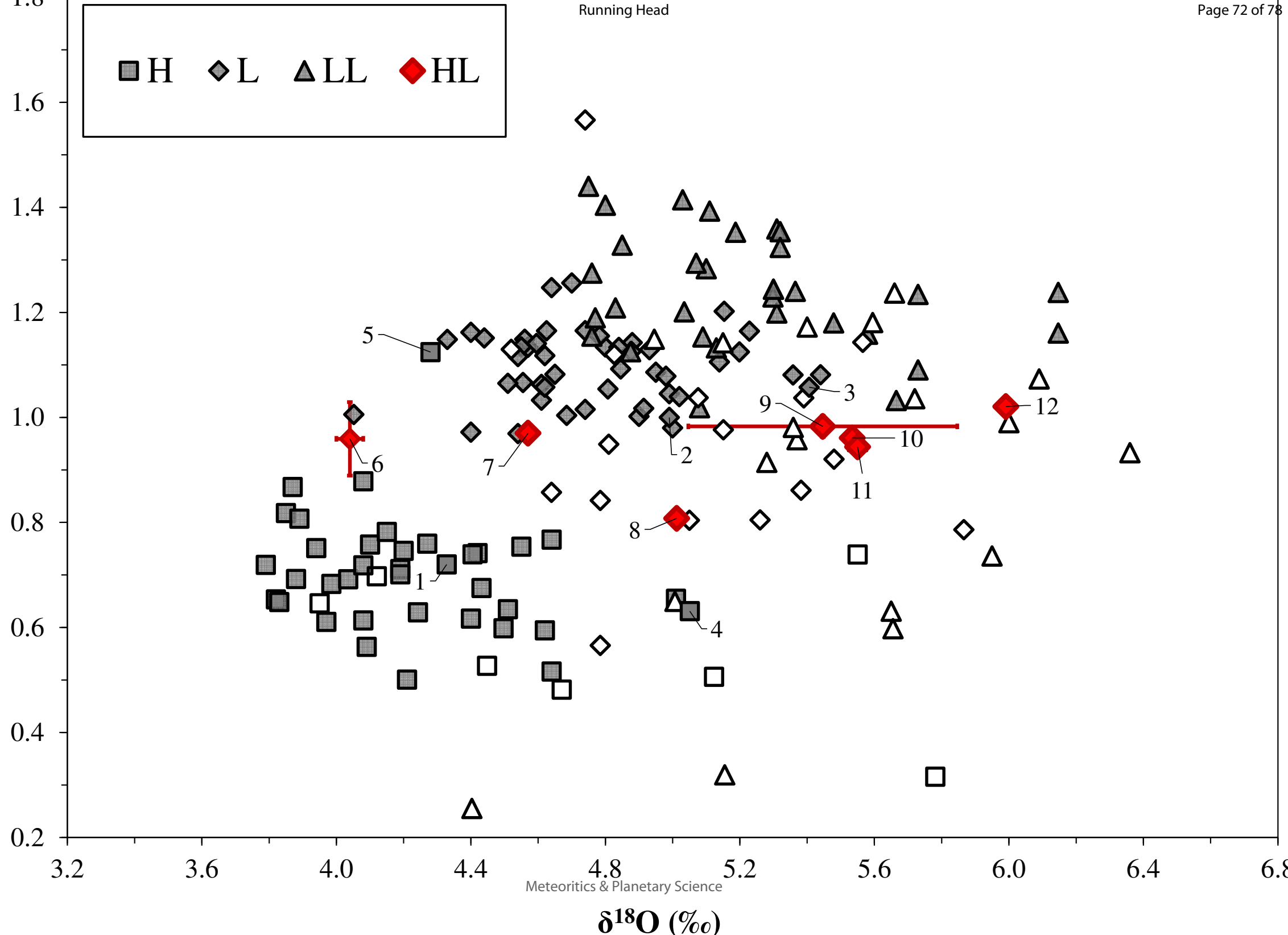
Normalized to mean CI chondrites

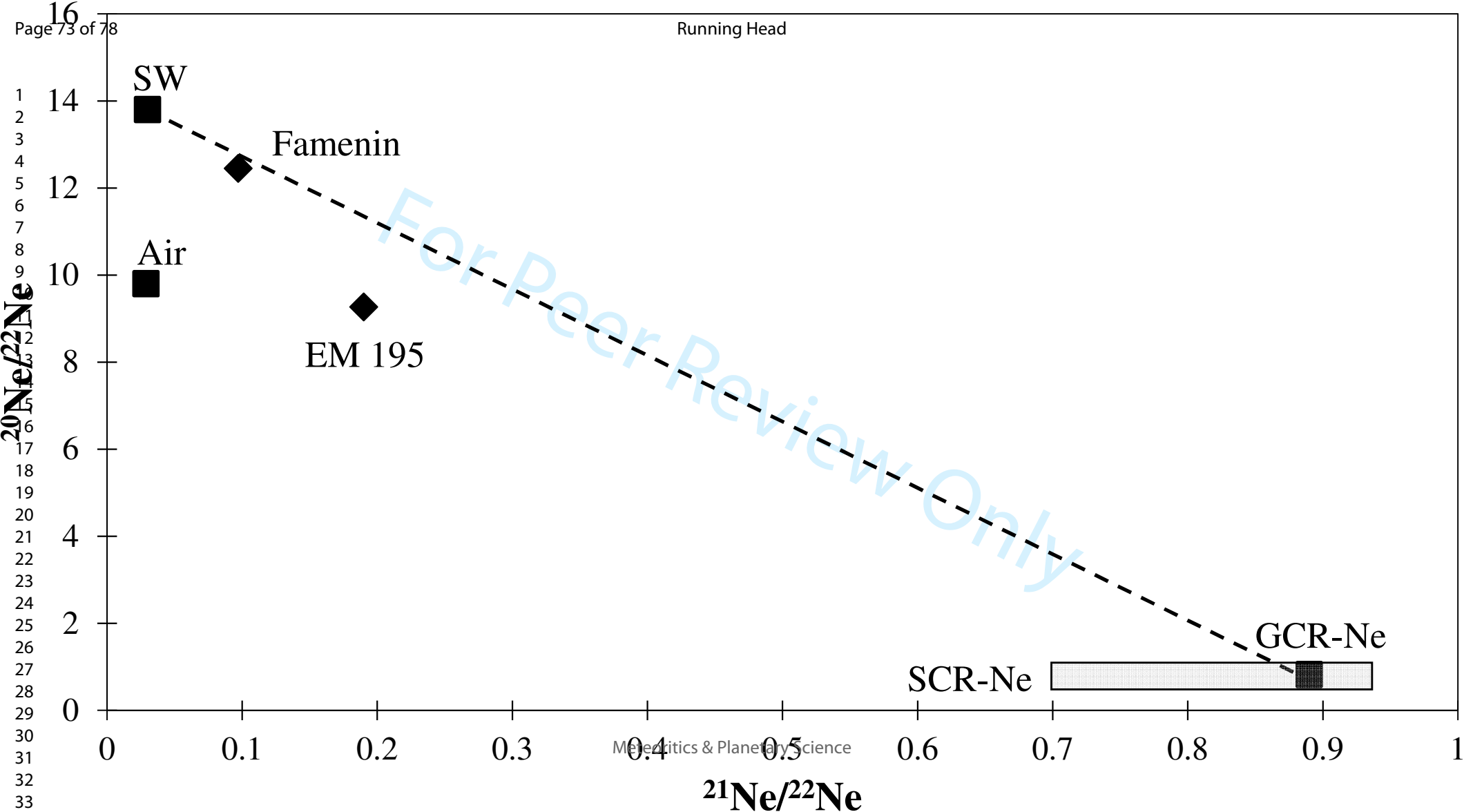


Decreasing volatility →

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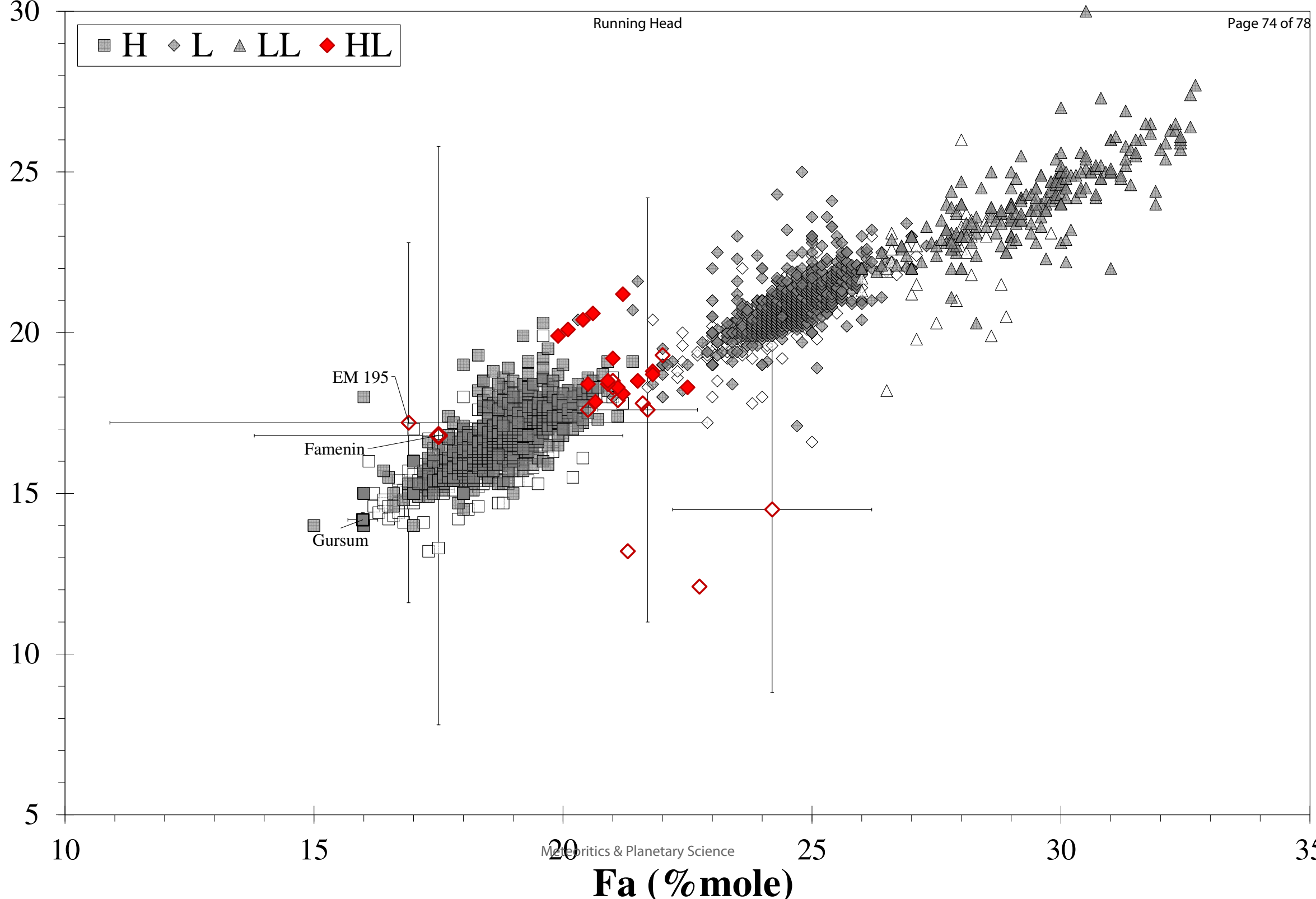




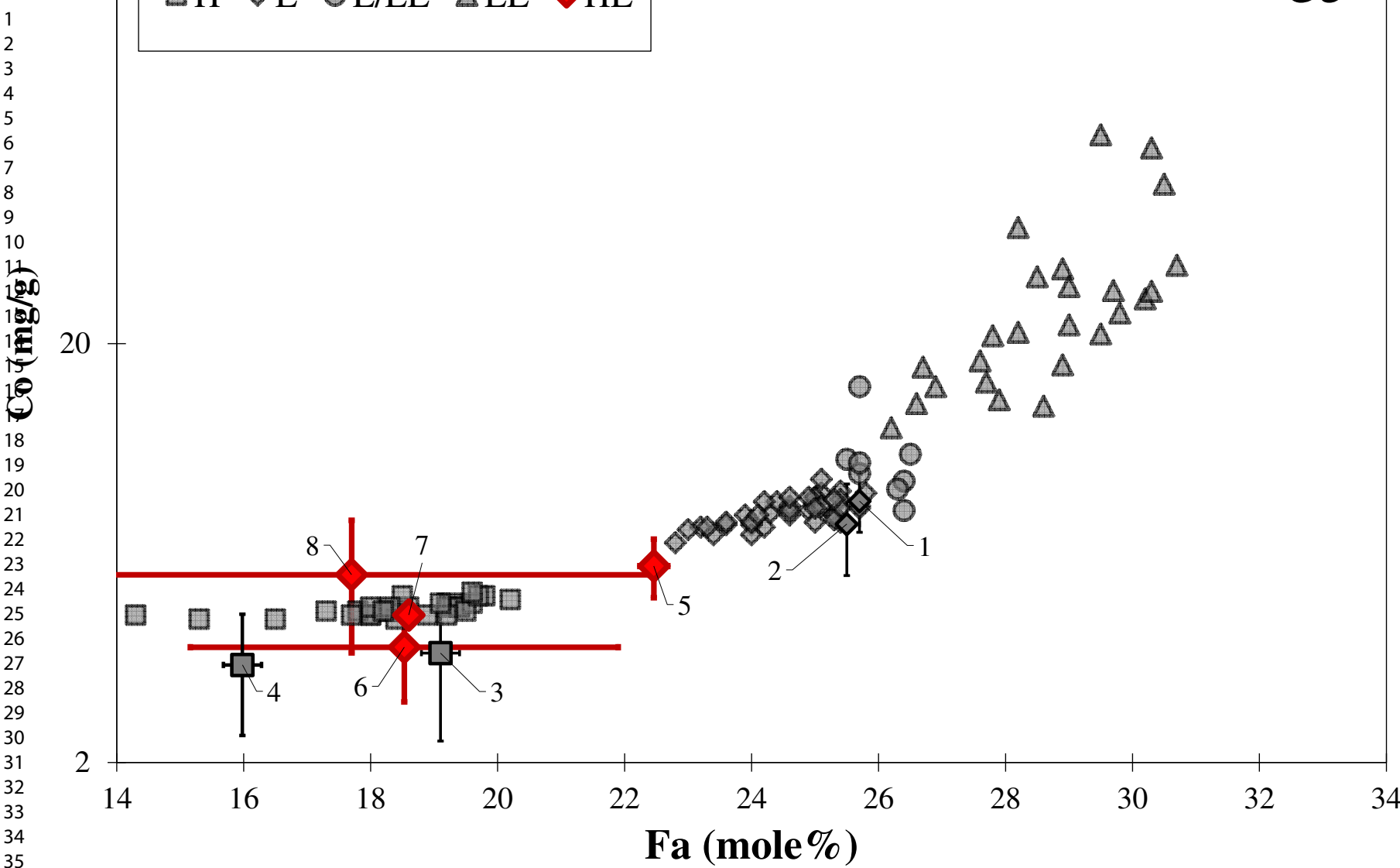
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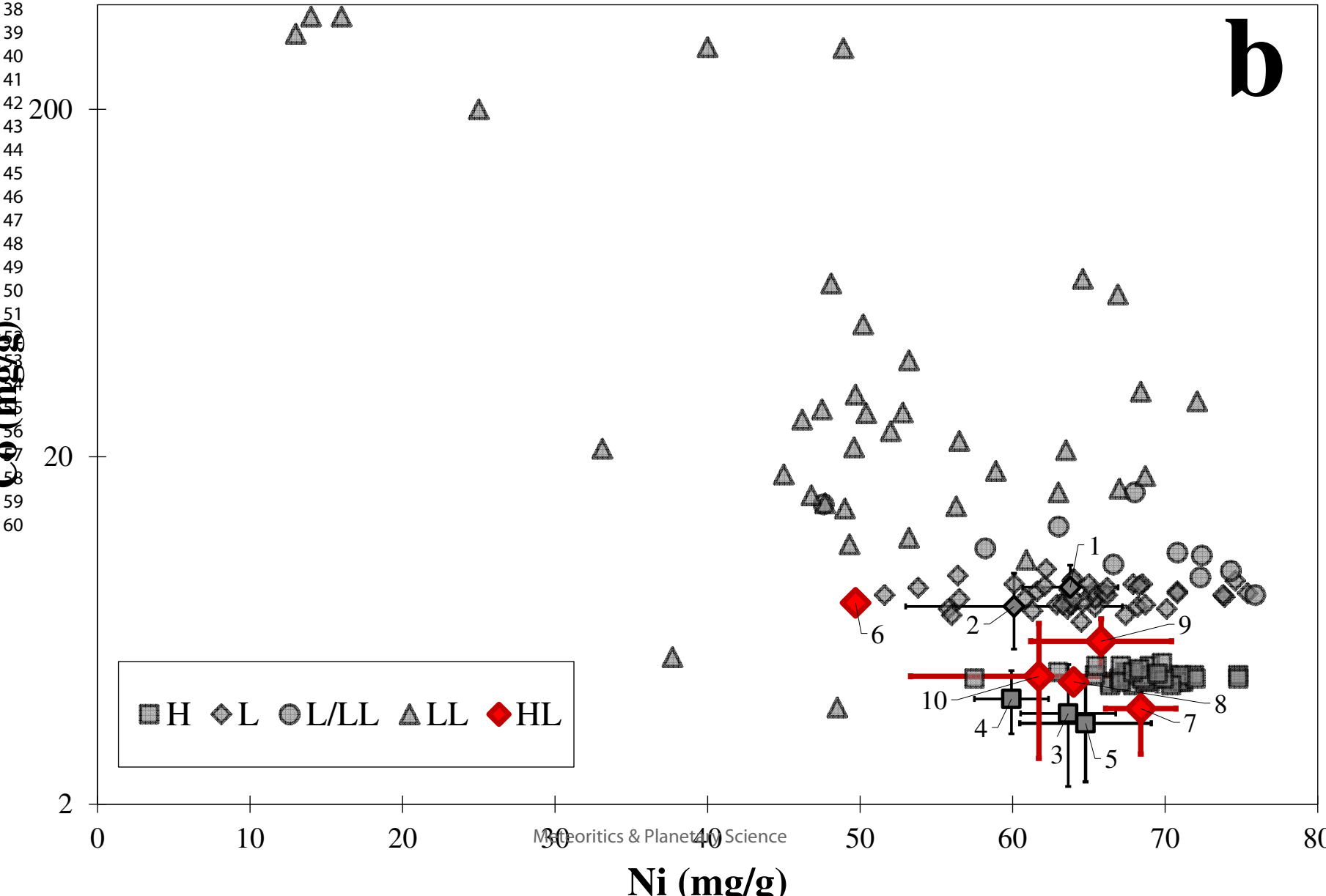
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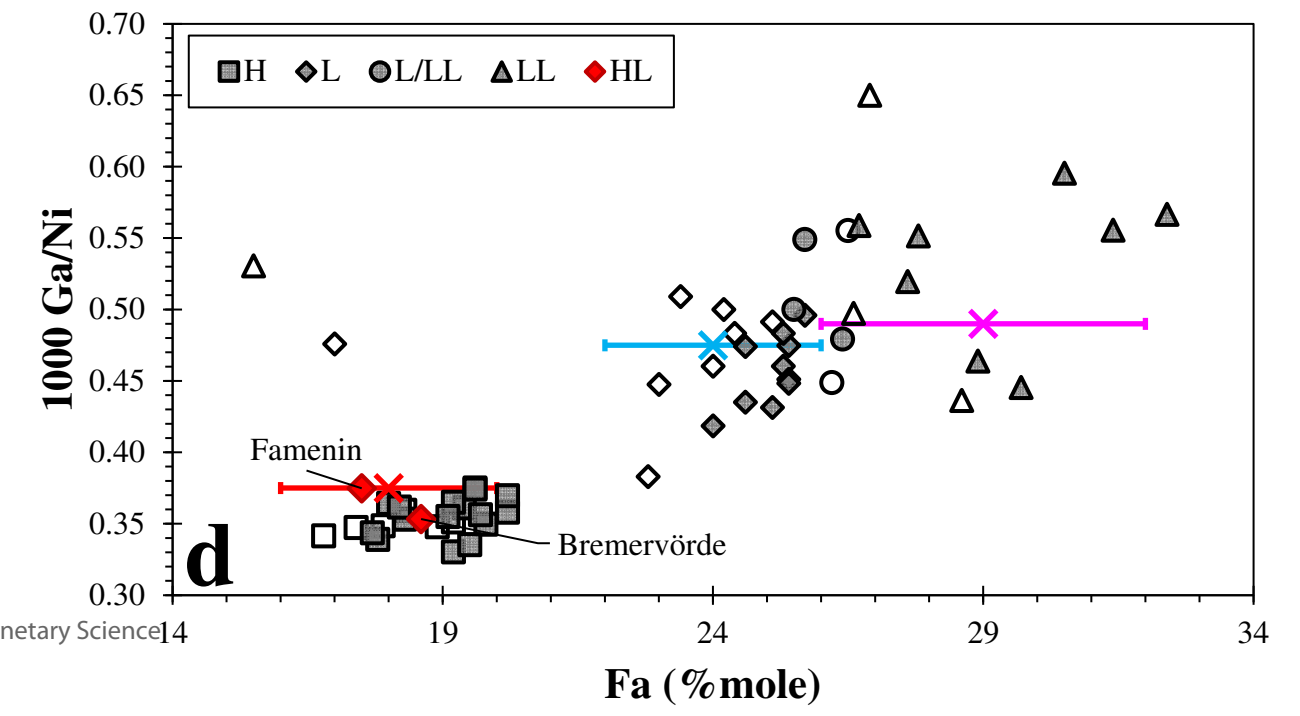
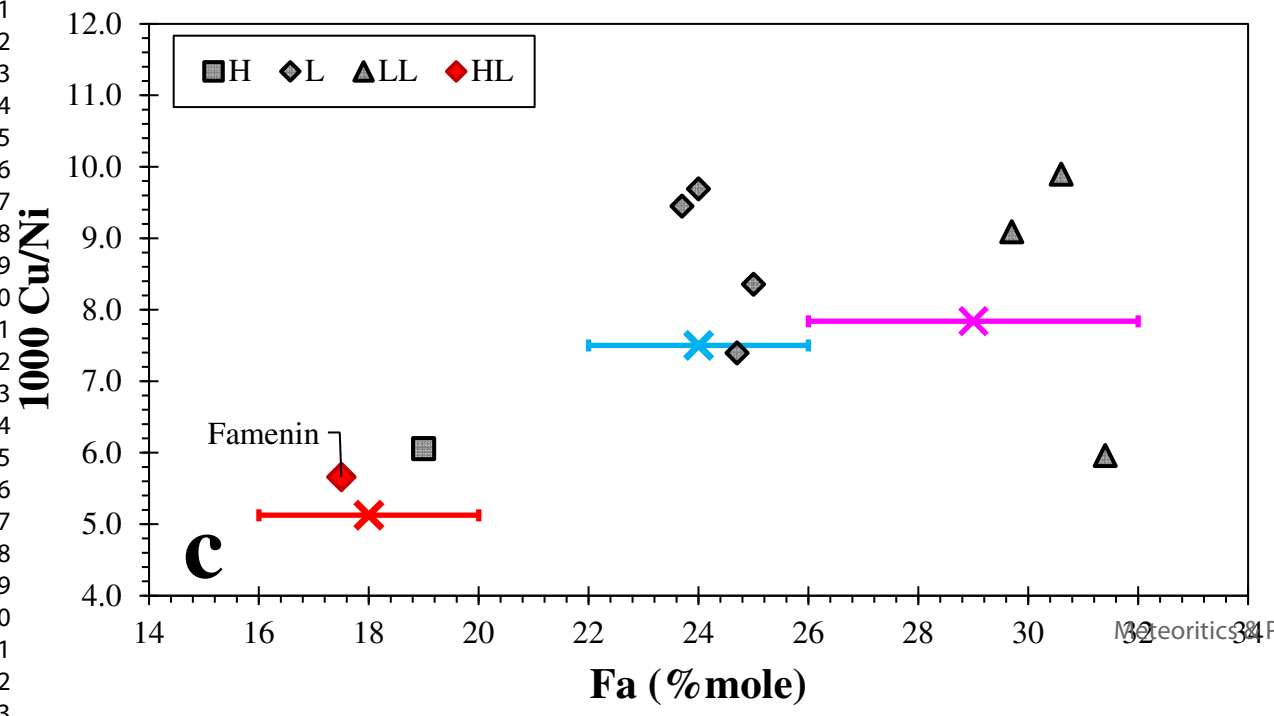
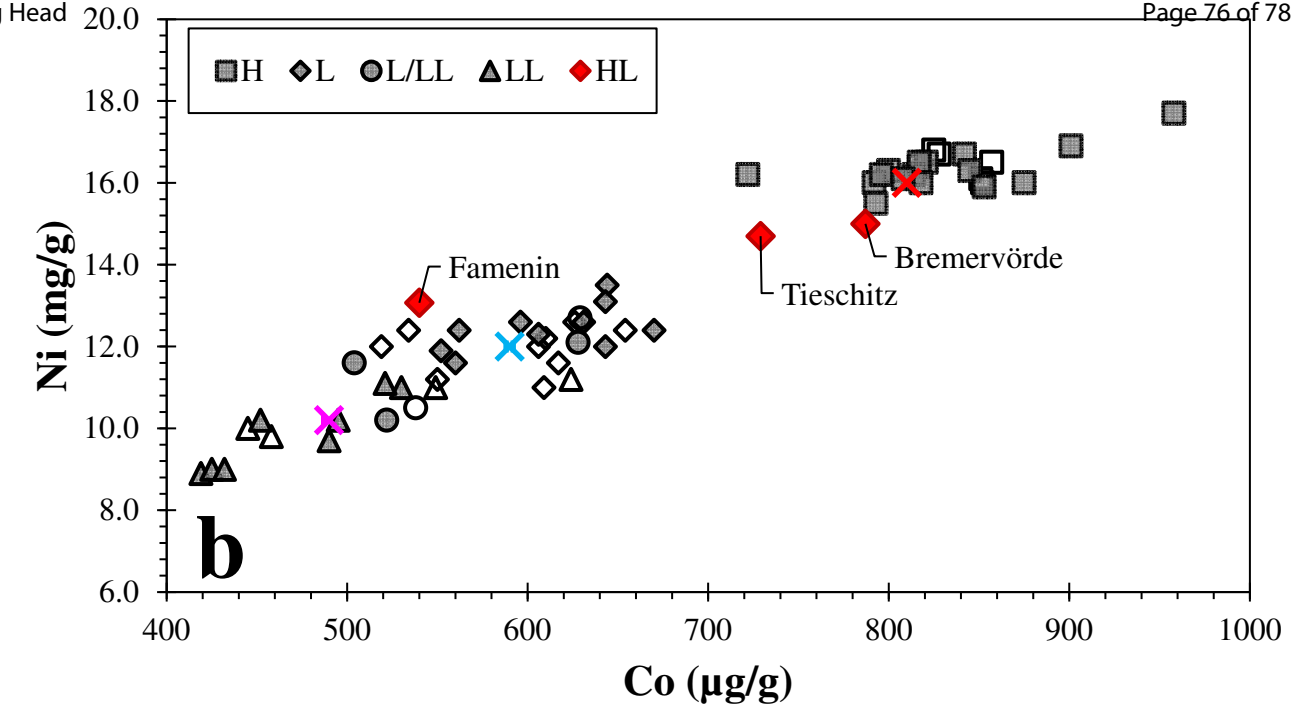
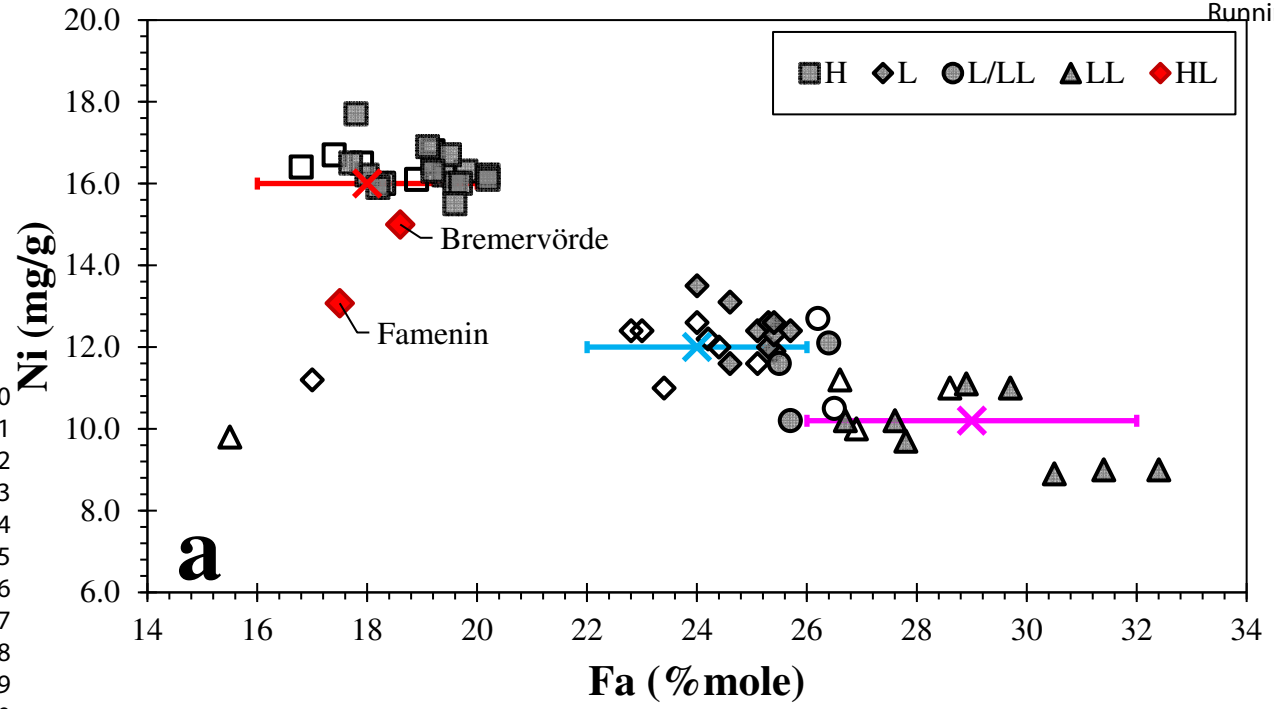


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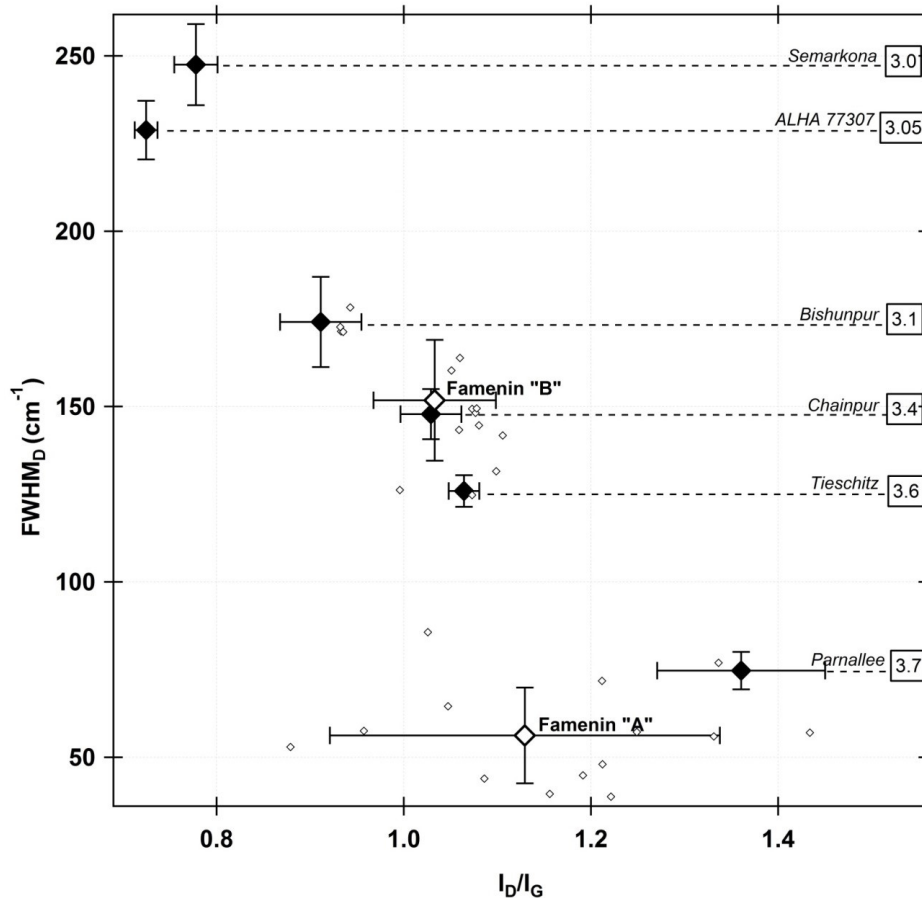


Fig. 12: Spectral parameters of Raman bands of carbonaceous materials in Famenin and in reference chondrites: $FWHM_D$ vs. I_D/I_G . Averages (points) and standard deviations (bars) are plotted for reference samples (black symbols) and for Famenin (open symbols). Spectral parameters of individual spectrum are plotted for Famenin (small grey diamonds). Reference chondrites data from Bonal et al. (2016).

160x144mm (220 x 220 DPI)

