



HAL
open science

Tintigny meteorite: the first Belgian achondrite

Hamed Pourkhorsandi, Vinciane Debaille, J. Gattacceca, Richard Greenwood,
Thierry Leduc, Marleen de Ceukelaire, Sophie Decrée, Steven Goderis

► **To cite this version:**

Hamed Pourkhorsandi, Vinciane Debaille, J. Gattacceca, Richard Greenwood, Thierry Leduc, et al..
Tintigny meteorite: the first Belgian achondrite. *Planetary and Space Science*, 2021, 209, pp.105372.
10.1016/j.pss.2021.105372 . insu-03517363

HAL Id: insu-03517363

<https://insu.hal.science/insu-03517363>

Submitted on 18 Jan 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Journal Pre-proof



Tintigny meteorite: The first Belgian achondrite

Hamed Pourkhorsandi, Vinciane Debaille, Jérôme Gattacceca, Richard Greenwood, Thierry Leduc, Marleen De Ceukelaire, Sophie Decrée, Steven Goderis

PII: S0032-0633(21)00211-7

DOI: <https://doi.org/10.1016/j.pss.2021.105372>

Reference: PSS 105372

To appear in: *Planetary and Space Science*

Received Date: 19 March 2021

Revised Date: 18 October 2021

Accepted Date: 27 October 2021

Please cite this article as: Pourkhorsandi, H., Debaille, V., Gattacceca, Jéô., Greenwood, R., Leduc, T., De Ceukelaire, M., Decrée, S., Goderis, S., Tintigny meteorite: The first Belgian achondrite, *Planetary and Space Science* (2021), doi: <https://doi.org/10.1016/j.pss.2021.105372>.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2021 Published by Elsevier Ltd.

Title: Tintigny meteorite: the first Belgian achondrite

Authors: Hamed Pourkhorsandi^{a,4}, Vinciane Debaille^a, Jérôme Gattacceca^b, Richard Greenwood^c, Thierry Leduc^d, Marleen De Ceukelaire^d, Sophie Decrée^d, and Steven Goderis^e

^aLaboratoire G-Time, Université Libre de Bruxelles, CP 160/02, 50, Av. F.D. Roosevelt, 1050 Brussels, Belgium

^bCNRS, Aix-Marseille Univ, IRD, INRAE, CEREGE, Aix-en-Provence, France

^cSchool of Physical Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, United Kingdom

^dRoyal Belgian Institute of Natural Sciences, Geological Survey of Belgium, 1000 Brussels, Belgium

^eDepartment of Chemistry, Research Unit: Analytical, Environmental and Geo-Chemistry, Vrije Universiteit Brussel, Brussels, 1050, Belgium

⁴Corresponding author. *E-mail address:* hamed.pourkhorsandi@ulb.ac.be

Revision to be submitted to the *Planetary and Space Science (Planet Space Sci.)*

Version: 18/10/2021

1 Abstract:

2 A late afternoon in February 1971, a meteorite impacted the rooftop of a house
3 in Tintigny village in southern Belgium. Confirmed as a possible meteorite by
4 the schoolteacher, the meteorite and its fall story did not leave the village.
5 Finally, 46 years after the fall event, we got the opportunity to study and
6 characterize this meteorite. In this work, we give a detailed report on its
7 textural, mineralogical, whole-rock elemental and oxygen isotopic composition.
8 Officially named as Tintigny, we classified it as an achondrite from howardite-
9 eucrite-diogenite (HED) clan and more precisely a polymict eucrite. A
10 brecciated basaltic rock believed to be originated from the surface of V-type
11 asteroids namely the asteroid 4-Vesta. Tintigny has recorded the evidence of
12 the impact metamorphism and metasomatism processes active on its parent
13 body. Tintigny is one of the 39 eucrite falls known to date, and one of the 11
14 eucrites occurred in Europe. It is the fifth officially recognized meteorite and
15 the first achondrite from Belgium. This report shows the importance of studying
16 and accessing such a meteorite for further cosmochemical and planetary
17 investigations and enriching our knowledge on the formation of HED
18 meteorites and their parent bodi(es). In addition, it brings the attention to its
19 importance as a scientific heritage that has to be properly understood and
20 safeguarded for the generations of scientists, scholar, and amateurs to come

21 **Keywords:** Achondrite, Fall, Eucrite, Belgium, Tintigny

22

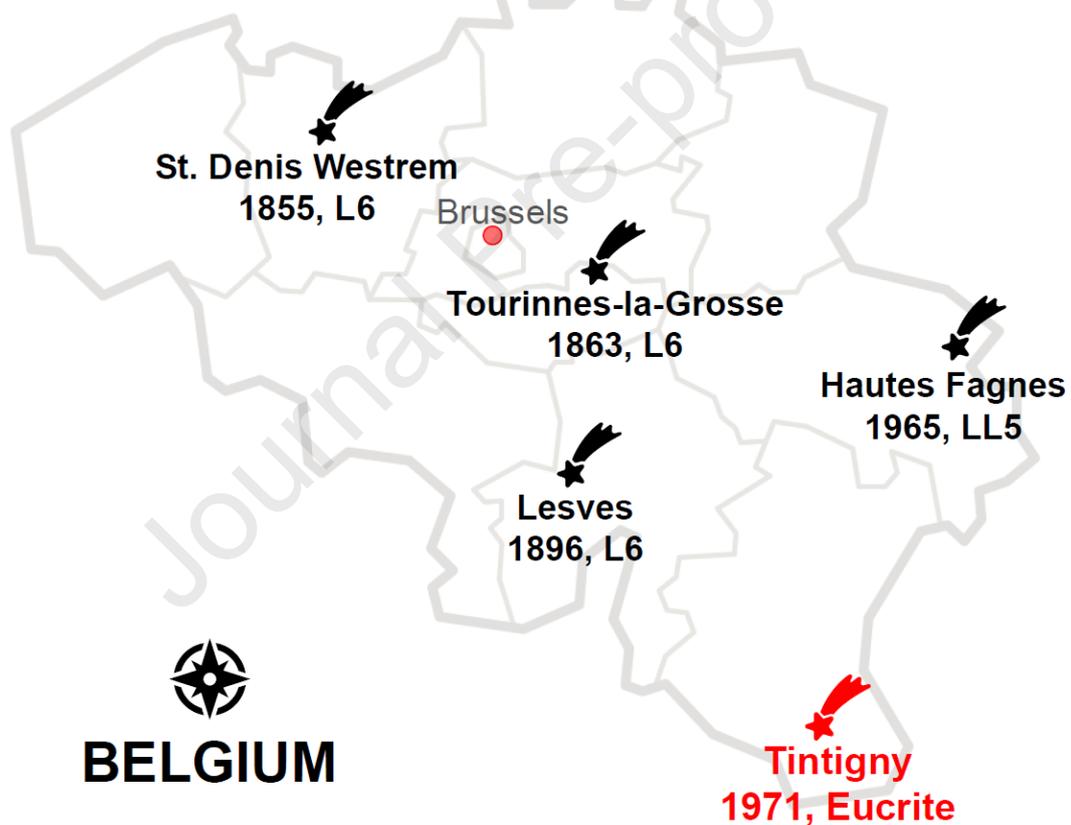
23

24 INTRODUCTION

25 In February 1971 (precise date not recorded), Mr Eudore Schmitz was
26 working in his barn in the village of Tintigny (southern Belgium, 49.683786°N,
27 5.532957°E) during the late afternoon when he heard a loud noise from the
28 roof of the building. After going upstairs, he found a hole in a tile and a black
29 stone on the barn floor. It was suggested that he burnt himself picking up the
30 fragment, so he used some hay and then his hat to hold the stone. The
31 schoolteacher of the village, Mr Albert Rossignon, confirmed that the stone
32 was a meteorite and kept it, hoping that his identification would be confirmed
33 during a subsequent investigation. The teacher later joined a religious
34 seminary and became a priest. While he faithfully kept the meteorite and
35 showed it from time to time to visitors and children, the stone and associated
36 story never left the region. In 2017, after reading an article about recent
37 Belgian meteorite recovery expeditions in Antarctica, he contacted Dr Vinciane
38 Debaille, professor at the Université Libre de Bruxelles (ULB) and specialist in
39 planetary sciences and meteoritics who recognized the stone as an achondritic
40 meteorite. The meteorite was subsequently donated by Madam Germaine
41 Mathus, widow of Mr Eudore Schmitz, and her children, Jean-Paul, Rita and
42 Joseph Schmitz, to the Royal Belgian Institute for Natural Science (RBINS)
43 and studied. While the meteorite is no longer complete due to handling of the
44 stone by various people over the years, Father Rossignon affirms that the
45 fusion crust was initially complete, with a piece of the tile originally stuck on the
46 stone.

47 We have classified this meteorite as a polymict eucrite and Tintigny, its
48 official name, has been approved by the Nomenclature Committee of the
49 Meteoritical Society (Gattacceca et al., 2020). Tintigny is the fifth officially
50 recognized meteorite and the first achondrite from the Belgian territory (Fig. 1).
51 This meteorite is now on permanent open display at RBINS.

52 In this paper, details on the petrological, geochemical, and isotopic
53 characteristics of Tintigny are reported and its formation processes studied.



54

55

56

Figure 1: Meteorites of Belgium with fall/find years and types.

57

58 **METHODOLOGY**

59 Following examination of the whole rock using a stereomicroscope,
60 representative fragments covering all petrographic textures were separated
61 and embedded in resin at RBINS. Mineralogical and petrological studies were
62 conducted using an optical microscope (ULB) and a PANalytical (Quanta 200)
63 equipment Environmental Scanning Electron Microscope (ESEM) equipped
64 with an EDAX (Apollo 10 silicon drift detector) Energy Dispersive Spectrometer
65 (EDS) at the RBINS. The chemical composition of mineral phases were
66 determined using a CAMECA SX50 electron microprobe (EMP) at the
67 CAMPARIS facility (Paris), relying on a series of natural and synthetic
68 standards and a later correction for SiO₂ calibration. The set instrument
69 parameters include a focused electron beam (~ 1 µm in diameter), an
70 accelerating voltage of 15 kV and a beam current of 10 nA. We aimed to
71 analyze pyroxene and plagioclase with diverse compositions. Special care was
72 considered to avoid grain boundaries, cracks etc. which can bias the quality of
73 the analytical data. Whole-rock major and trace elemental concentrations were
74 determined at the Laboratoire G-Time of the ULB, Belgium. Around 50 mg of
75 sample representing the most common lithology (light grey) of the meteorite,
76 was dissolved by alkaline fusion for major and trace element contents. Major
77 elements were measured using a Thermo Fisher Scientific iCAP inductively
78 coupled plasma-optical emission spectrometer (ICP-AES) at ULB with Y as an
79 internal standard. Overall, the total reproducibility estimated based on United
80 States Geological Survey reference material BHVO-2 is calculated to be better
81 than 2% relative standard deviation (RSD). Trace elements were measured

82 using the Agilent 7700 Quadrupole-Inductively Coupled Plasma-Mass
83 Spectrometer (Q-ICP-MS) operated with a He-filled collision cell at ULB.
84 Indium was used as internal standard. The total reproducibility estimated
85 based on USGS reference material BHVO-2 is calculated to be better than
86 10% relative standard deviation (RSD).

87 High-precision oxygen isotopic analysis of Tintigny was undertaken at the
88 Open University (Milton Keynes, UK) using an infrared laser-assisted
89 fluorination system (Miller et al., 1999; Greenwood et al., 2017).
90 Measurements were made on a 200 mg aliquot of silicates from the bulk
91 sample. Approximately 2 mg aliquots of samples and standards were loaded
92 into a nickel sample block, which was then placed in a two-part chamber,
93 made vacuum tight using a compression seal with a copper gasket and quick-
94 release KFX clamp (Miller et al., 1999). A 3 mm thick BaF₂ window at the top
95 of the chamber allows simultaneous viewing and laser heating of samples.
96 Prior to analysis the sample chamber was heated overnight under vacuum to a
97 temperature of about 70°C to remove any adsorbed moisture. Following
98 overnight heating, the chamber was allowed to cool to room temperature and
99 was then flushed with several aliquots of BrF₅. The system was then left to
100 pump for at least a further 24 hours and oxygen isotopic analysis was only
101 undertaken when the blank level reached <60 nanomoles of O₂. Sample
102 heating in the presence of BrF₅ was carried out using a Photon Machines Inc.
103 50W infrared CO₂ laser (10.6 μm) mounted on an X-Y-Z gantry. Reaction
104 progress was monitored by means of an integrated video system. After

105 fluorination, the released O₂ was purified by passing it through two cryogenic
106 nitrogen traps and over a bed of heated KBr to remove any excess fluorine.
107 The isotopic composition of the purified oxygen gas was analyzed using a
108 Thermo Fisher MAT 253 dual inlet mass spectrometer with a mass resolving
109 power of approximately 200.

110 Overall system precision, as defined by replicate analyses of our internal
111 obsidian standard, is: ±0.053‰ for δ¹⁷O; ±0.095‰ for δ¹⁸O; ±0.018‰ for Δ¹⁷O
112 (2σ) (Starkey et al., 2016). Oxygen isotopic analyses are reported in standard
113 δ notation, where δ¹⁸O has been calculated as: δ¹⁸O = [(¹⁸O/¹⁶O)_{sample}/¹⁸O
114 /¹⁶O)VSMOW -1] 1000 (‰) and similarly for δ¹⁷O using the ¹⁷O/¹⁶O ratio.
115 VSMOW is the international standard Vienna Standard Mean Ocean Water.
116 Δ¹⁷O, which represents the deviation from the terrestrial fractionation line, has
117 been calculated using the linearized format of Miller (2002):

$$\Delta^{17}\text{O} = 1000\ln(1 + (\delta^{17}\text{O}/1000)) - \lambda 1000\ln(1 + (\delta^{18}\text{O}/1000)) \text{ where } \lambda =$$

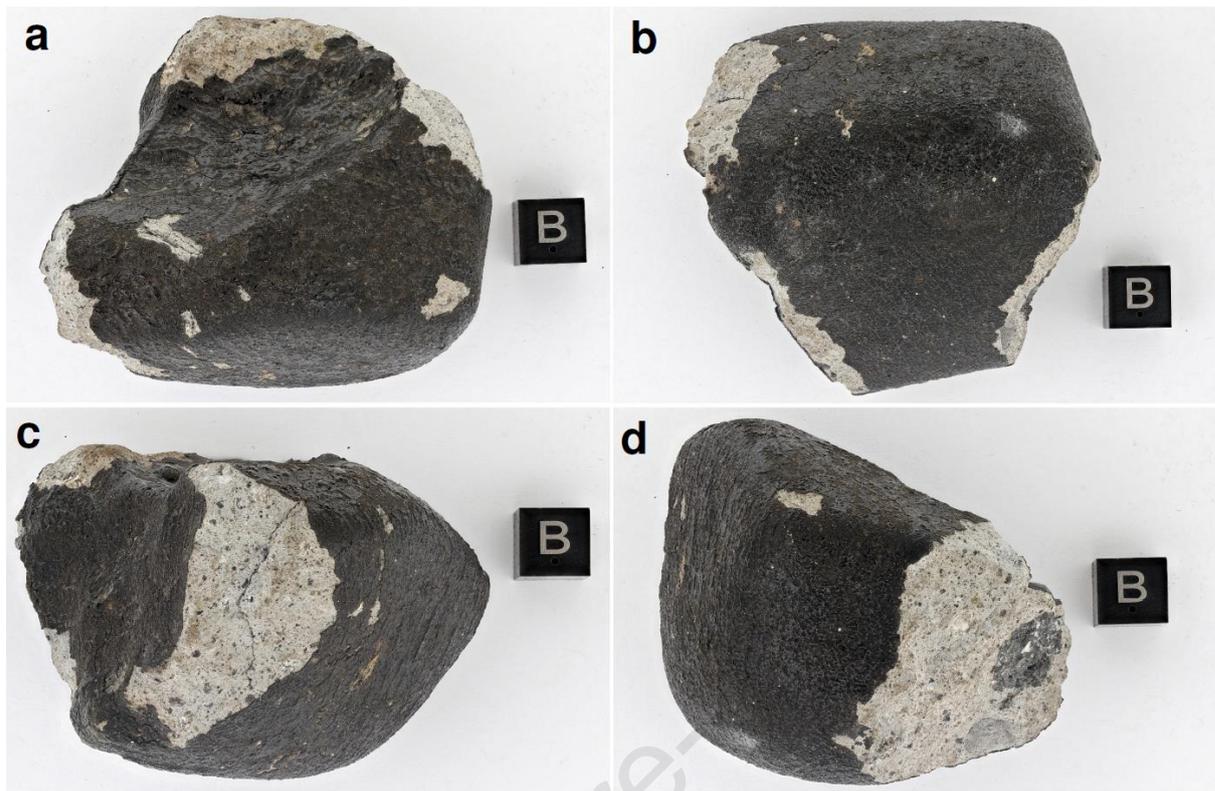
118
119 0.5247.

120 RESULTS

121 Macroscopic description

122 As a result of the thermal effects experienced during atmospheric entry and
123 impact through the roof of the building, the Tintigny meteorite finally
124 fragmented into several pieces during its extensive manual handling alongside
125 fractures, indicated by the occurrence of broken surfaces. The single
126 recovered fragment weighs 210 g (Fig. 2).

127 The meteorite is partly covered by a shiny black fusion crust, which varies in
128 thickness depending on the morphology of the underlying surface. Three main
129 varieties of fusion crust are present: (i) the thickest (~ 1-2 mm) parts that occur
130 in hollow areas of the surface and display a wavy texture comprising elevated
131 ribbons of molten material (flow lines) (Fig. 2a); (ii) the main part that is
132 considerably thinner (~ 0.5 mm) and indicates a full layer of molten material
133 with a texture containing assemblages of crater-like pits (Fig. 2b); (iii) the
134 intermediate part exhibiting a combination of these two variations, with a
135 patchy texture occurring along the edges of the meteorite surface. Several
136 cracks occur on the surface of the fusion crust. They correspond to deeper
137 fractures visible where the surface is broken (Fig. 2c). At these sites, a light
138 gray interior is revealed, composed of a fine-grained light-colored matrix
139 hosting darker crystals and a cm-size dark grey clast (Fig 2d). Macroscopic
140 observations indicate that Tintigny is a brecciated achondrite.



141

142 **Figure 2:** Tintigny meteorite from different angles. Note the different textures of fusion crust,
 143 the occurrence of fractures, and a dark grey clast in d. Image credit: RBINS.

144

145 **Microscopic description**

146 Using optical and electron microscopy, Tintigny exhibits a brecciated sub-
 147 ophitic basaltic texture mainly composed of plagioclase/maskelynite and
 148 clinopyroxene (Fig. 3). These minerals occur both as large crystals ($>50\mu\text{m}$)
 149 and as smaller ($<50\mu\text{m}$) ones, the latter mainly composing the clastic matrix.
 150 Accessory minerals include troilite, ilmenite, chromite, (Fe,Ni) metal, and silica.
 151 Most of the minerals exhibit well-delineated edges, enhancing the clastic
 152 texture of the rock. At least two generations of shock fractures are visible:

153 those specific to clasts and large crystals, and those cross-cutting both the
154 larger grains and the matrix materials.

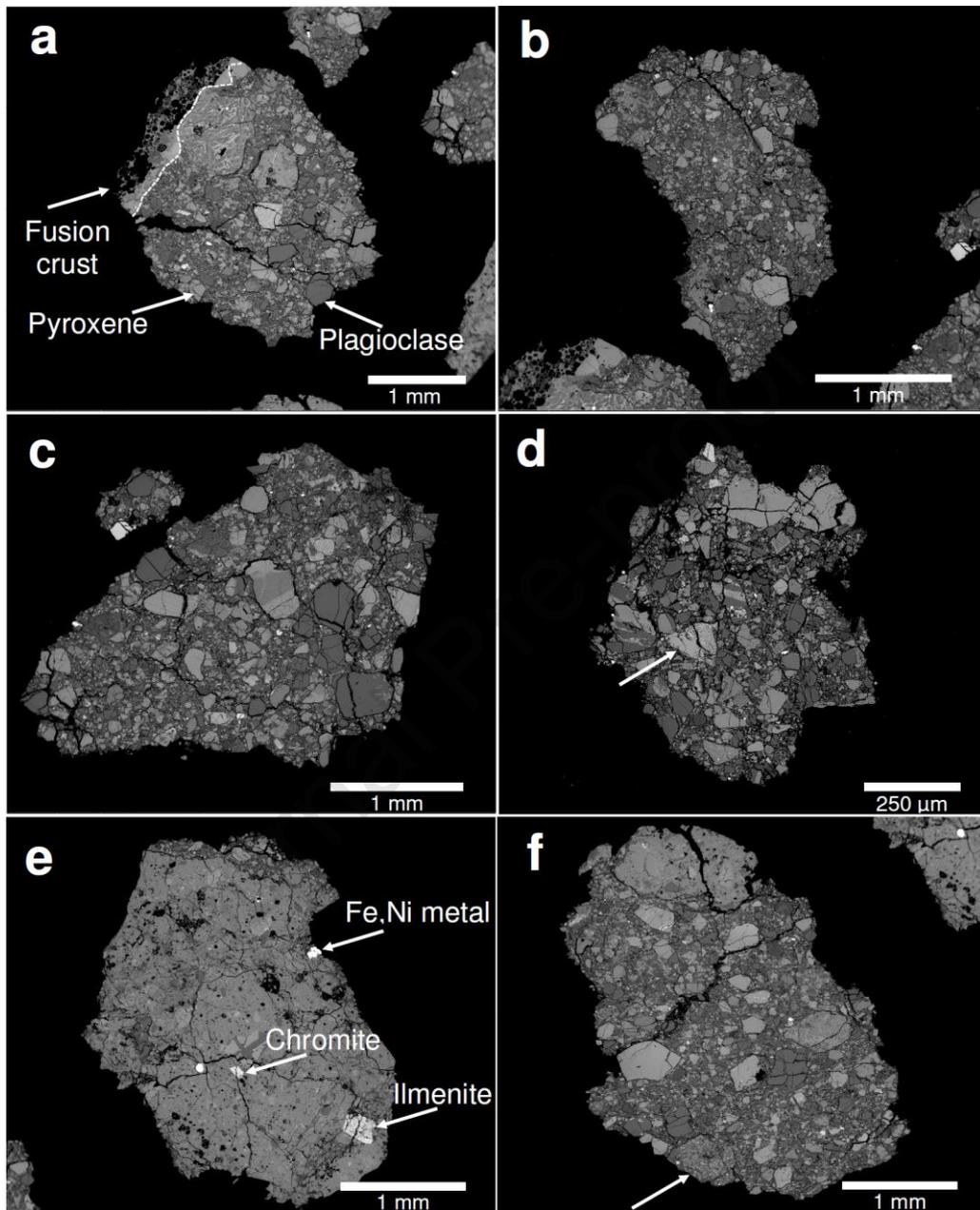
155 In addition to the main sub-ophitic texture, at least three distinct textures are
156 present in specific clasts. These clasts are different from their host based on
157 their texture and degree of equilibrium recorded in the composing minerals.
158 Figure 3a,4e shows a ~ 1 mm long clast with a sub-ophitic texture. Elongated
159 pyroxenes are unequilibrated and display Fe enriched rims. The elongation
160 directions of pyroxene crystals control the alignment of plagioclase. Abundant
161 cracks perpendicular to pyroxene elongation are visible. They are absent from
162 the adjacent plagioclase crystals, suggesting elevated levels of mechanical
163 stress prior plagioclase crystallization. Some of these plagioclase crystals are
164 cut by randomly oriented cracks, which are filled by Fe-rich pyroxenes. This is
165 related to fusion crust formation. Another clast with a similar texture is visible in
166 Fig. 3f.

167 Under the electron microscope, the dark clast visible on the broken surface
168 (Fig. 2d) displays a melt rock texture (Fig. 3e,4f). The groundmass is a mixture
169 of quenched pyroxene and plagioclase and only a few larger grains including
170 (Fe,Ni) metal, ilmenite, chromite, and an intergrowth of plagioclase-pyroxene
171 are present.

172 A single ~ 0.5 mm clast and several smaller grains exhibit a symplectitic
173 mixture of pyroxene, fayalite, and silica (Fig. 3a,c,d and Fig. 4b,d).

174 A small number of pyroxenes show evidence of Fe enrichment along veins
175 and crystal rims (Fig. 3f and Fig. 4b,e). These fractures are mostly limited to

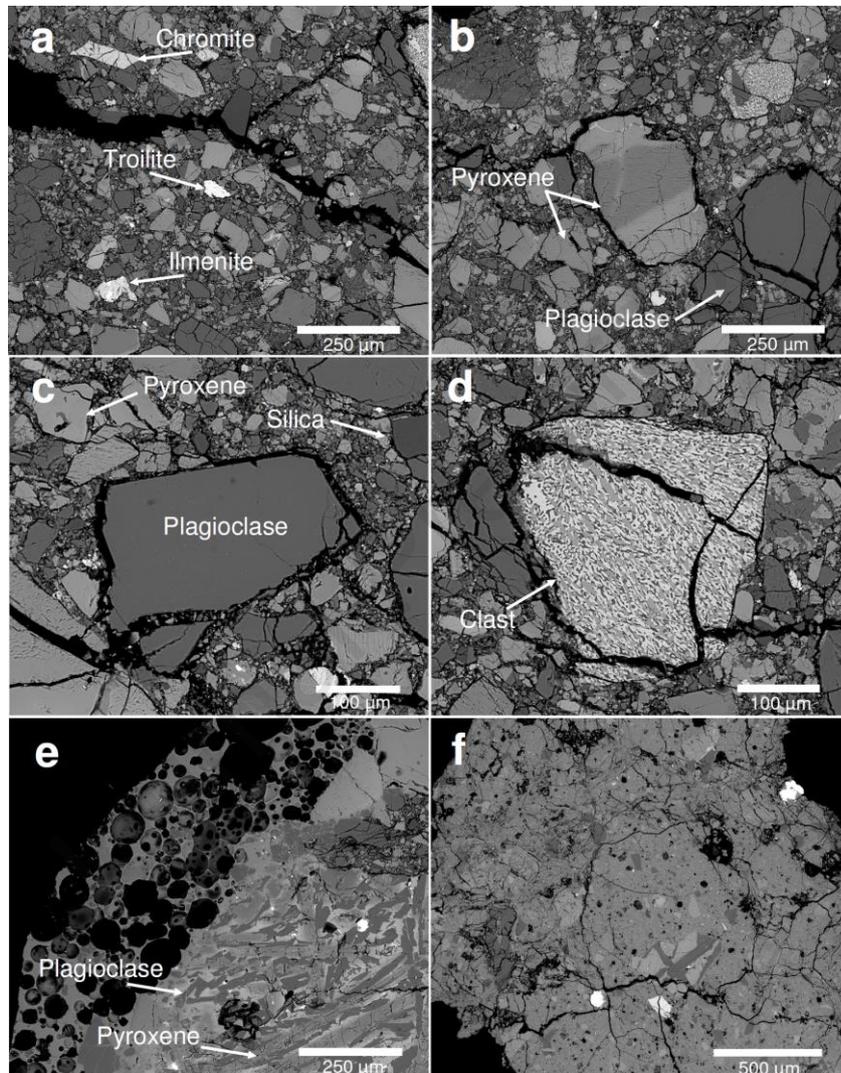
176 individual grains and do not occur in the whole rock, indicating their formation
 177 was prior to the assembly of Tintigny on its parent body.



178

179 **Figure 3:** Backscattered electron microscope images of Tintigny. The presence of different
 180 textures suggests Tintigny to be a brecciated eucrite. a) A sub-ophitic clast adjacent to the
 181 fusion crust shows a texture distinct from that of the host. In the center, a clast with a
 182 symplectitic texture is visible. b) Typical texture of Tintigny. A pyroxene with exsolution
 183 lamellae is visible. c) Variety of pyroxene textures including exsolution lamella and
 184 symplectitic assemblages. d) Partial transformation of pyroxene to a symplectitic assemblage

185 is visible in one clast (shown by arrow). e) Dark grey clast (also visible in Fig. 2d), showing
 186 textural evidence of melt rock. f) The occurrence of different clasts. Note Fe-rich veins in a ~
 187 500 μm pyroxene in upper left. A clast with relatively larger crystals (shown with arrow) with
 188 similar sub-ophitic texture to the clast shown in 3a and 4e.



189

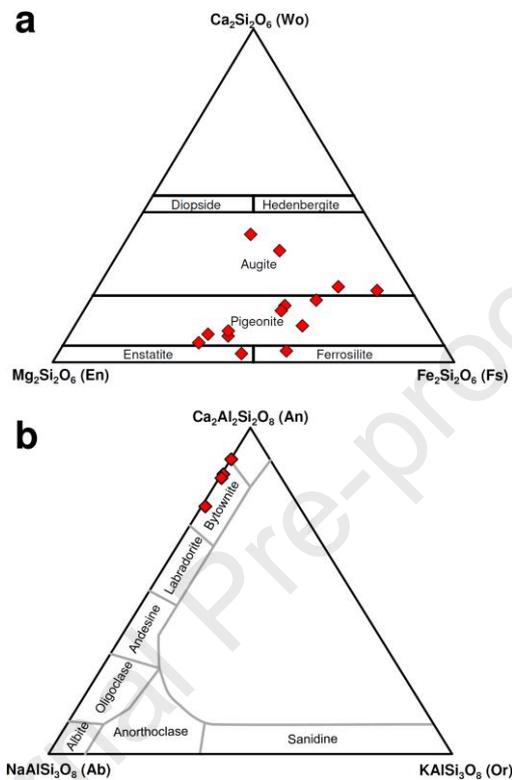
190 **Figure 4:** a) Accessory minerals in Tintigny. b) Pyroxene showing a variety of textures
 191 (exsolution, twinning, symplectitic, etc.), suggesting a complex thermal history experienced
 192 by the Tintigny. c) Clastic texture of Tintigny formed as a result of impact metamorphism on
 193 the parent body surface. d) A symplectitic assemblage of hedenbergite-fayalite-silica. e)
 194 Alignment of plagioclase along the surface of pyroxene. Note the higher concentration of Fe
 195 in pyroxene rims. f) A closer view of the dark grey clast (Fig. 2d) shows lower number of
 196 crystals and a shock-melted texture.

197 **Mineral chemistry**

198 Table 1 summarizes the chemical composition of pyroxene and plagioclase
199 crystals analyzed randomly in different fragments of Tintigny. Mineral
200 chemistry calculations of pyroxene end members show ranges from 8.5 to 60.7
201 mol% for enstatite, 30.1 to 70.0 mol% for ferrosilite, and 2.6 to 38.4 mol% for
202 wollastonite. Based on these values, most pyroxenes in Tintigny are pigeonite
203 and augite (Morimoto 1988; Marshall 1996) (Fig. 5a). The Fe/Mn ratios of
204 pyroxenes range from 27.1 to 39.3, with the highest ratio observed in pyroxene
205 from the symplectitic clast (Pyx #5, Table 1). Fe/Mn and Fe/Mg ratios in low-
206 Ca pyroxene ($Wo < 10$, Pyx #1,2,3,6,7,10) are 30.2 ± 4.4 and 0.8 ± 0.3 ,
207 respectively. These ratios in high-Ca pyroxene ($n=8$) are 34.3 ± 3.7 for Fe/Mn
208 and 2.6 ± 2.4 for Fe/Mg. The average pyroxene Fe/Mn ratio for all pyroxene is
209 32.5 ± 4.4 (SD, $n=14$). Fe/Mg ranges from 0.6 to 8.2, with an average value of
210 1.8 ± 2.0 (SD, $n=14$). Considering pyroxene Fe/Mn ranges of 40 ± 11 , 62 ± 18 ,
211 32 ± 6 , and 30 ± 2 for basaltic rocks from the Earth, Moon, Mars, and 4Vesta
212 (eucrites), respectively, and based on our data, particularly those of low-Ca
213 pyroxene, Tintigny falls in the range of basaltic eucrites (Papike et al., 2003).
214 We believe the higher standard deviation of our data results from a higher
215 diversity and relatively lower number of the analyzed minerals.

216 The anorthite content of four analyzed plagioclase ranges from 75.8 to 90.3
217 mol%. Plagioclase in the symplectitic clast, with 75.8 mol% anorthite, is less
218 calcic (and more sodic) than the host (Fig. 5b). Excluding this clast, the
219 anorthite percentage averages to 86.8 ± 3.4 mol% (SD, $n=3$). This value is in

220 range of both vestan (87 ± 2 mole%) and lunar rocks (89 ± 3 mole%) (Papike et
 221 al., 2003), however the Fe/Mn ratio of pyroxene indicates that Tintigny is a
 222 member of the HED suit.

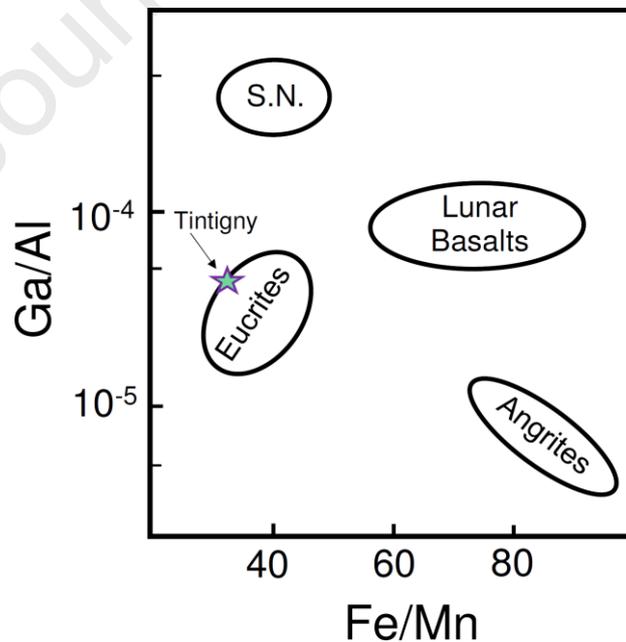


223
 224 **Figure 5:** Pyroxene and plagioclase compositions in Tintigny.

225 226 **Whole-rock chemical composition**

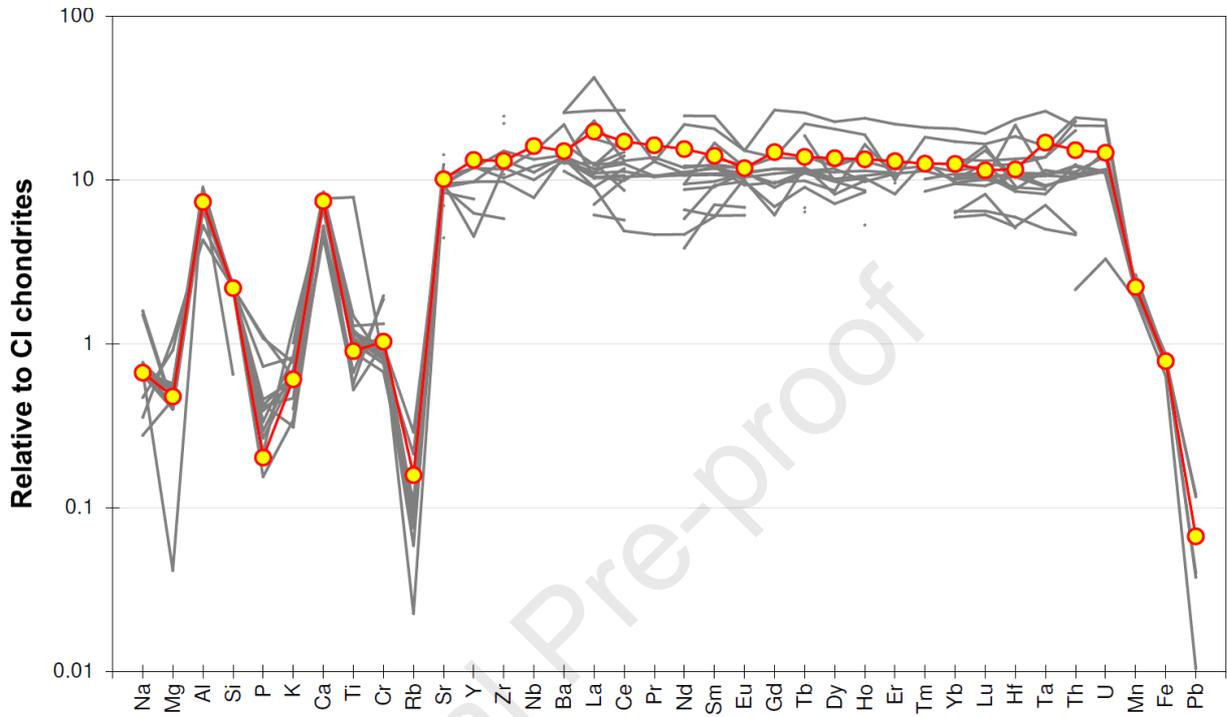
227 Table 2 shows the major and trace element concentrations of Tintigny.
 228 Based on bulk rock Fe/Mn vs. Fe/Mg ratios, three distinct zones for chondrites,
 229 lunar rocks, and howardite-eucrite-diogenite (HED)/Martian meteorites can be
 230 defined (Goodrich & Delaney, 2000). For Tintigny, the bulk rock Fe/Mn and
 231 Fe/Mg ratios are 33.9 and 3.1, respectively. These values overlap with those
 232 measured for HED and Martian meteorites. To discriminate between different

233 types of basaltic achondrites, Fe/Mn has previously been combined with other
 234 useful ratios such as Ga/Al (Barrat et al., 2003). The Ga/Al ratio of Tintigny is
 235 4.17×10^{-5} , fully in range of those of eucrites (Fig. 6). The CI-normalized
 236 elemental concentrations for Tintigny are compared to those of 18
 237 noncumulate eucrites in Fig 7. The latter plot indicates the strong similarities
 238 between the chemical composition of Tintigny and that of noncumulate
 239 eucrites. This similarity to eucrites is also evident based on various
 240 combinations of major and trace elements for HED. On a binary plot of Ca
 241 versus Mg, Tintigny overlaps with eucrites, but is distinct from howardites or
 242 diogenites (Fig. 8). Similar behavior occurs in Sm versus Mg and Yb versus La
 243 plots. Based on the abundance of TiO_2 (0.63%) and FeO/MgO ratio (2.66),
 244 Tintigny is a member of non-cumulate eucrites (Fig. 9) (Barrat et al., 2003).
 245

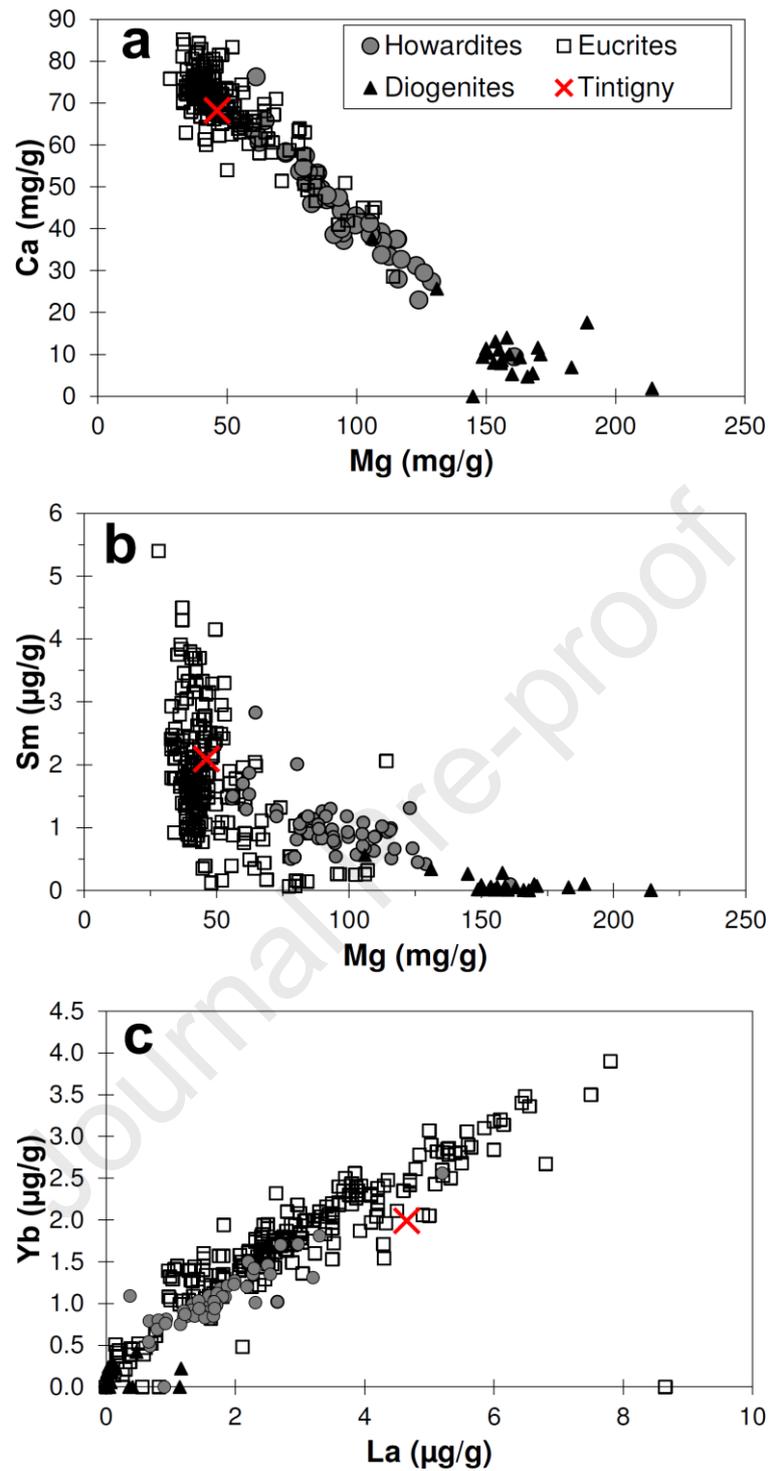


246

247 **Figure 6:** Ga/Al vs. Fe/Mn of Tintigny in comparison to other basaltic meteorites. Plot
 248 modified from Barrat et al. (2003). S.N. stands for shergottites and nakhlites clan of Martian
 249 meteorites.



250
 251 **Figure 7:** CI-normalized whole-rock chemical composition of Tintigny and 18 noncumulate
 252 eucrites (Béréba, Bouvante, Cachari, Chervony Kut, Elephant Moraine A79004,A79005,
 253 Haraiya, Ibitira, Junzac, Juvinas, Millbillillie, Moore County, Pasamonte, Pomozdino, Yamato
 254 794002,791573,82049,82202). Eucrite data from Kitts & Lodders (1998), Mittlefehldt (2015).
 255 Average CI chondrite data are from Wasson & Kallemeyn (1988). Lithophile, siderophile, and
 256 chalcophile elements are shown with increasing atomic number, respectively.



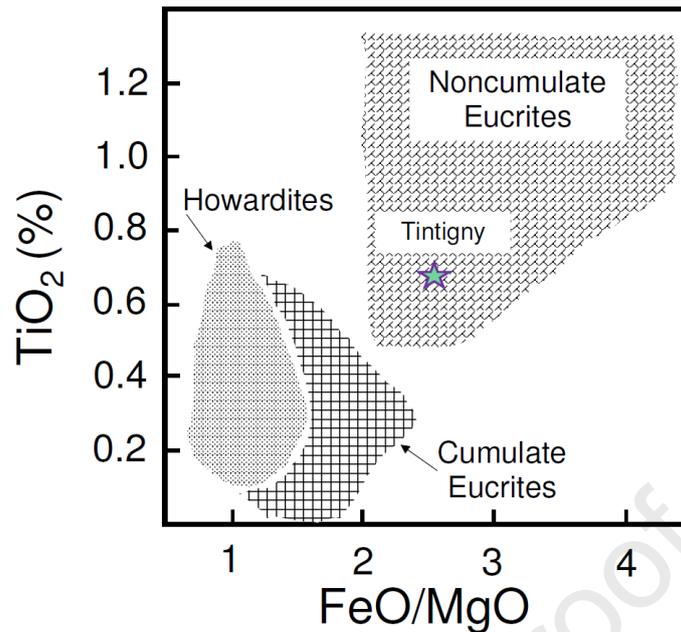
257

258 **Figure 8:** The abundance of Mg vs. Ca, Mg vs. Sm., and La vs. Yb for Tintigny in relation to

259 howardite-eucrite-diogenite (HED) meteorites. Compilation of HED data by Mittlefehldt

260

(2015).



261

262 **Figure 9:** TiO₂ vs. FeO/MgO of Tintigny in comparison to howardite and eucrites. Plot

263

modified from Barrat et al. (2003).

264

265 Oxygen isotopic composition

266 Two replicate analyses Tintigny gave the following oxygen isotopic: $\delta^{17}\text{O} =$

267 1.723 ± 0.018 (1σ); $\delta^{18}\text{O} = 3.756 \pm 0.041$ (1σ) and $\Delta^{17}\text{O} = -0.246 \pm 0.003$ (1σ).

268 The oxygen isotope data for Tintigny are plotted in relation to the HED data of

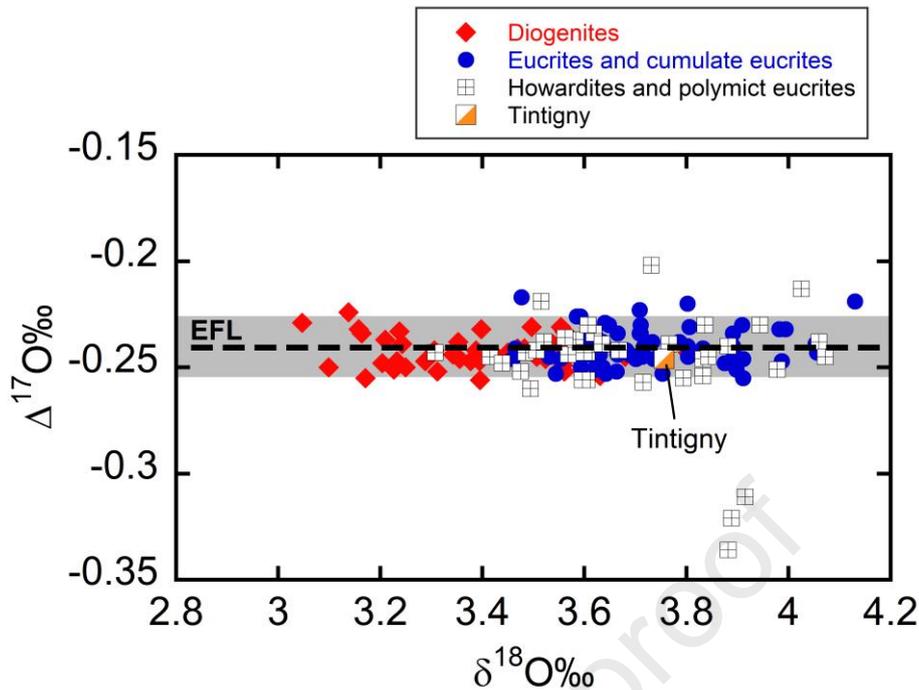
269 Greenwood et al. (2017) in Fig. 10 and this shows that the meteorite lies close

270 to the Eucrite Fractionation Line (EFL) defined by eucrite and diogenite falls

271 ($\Delta^{17}\text{O} = -0.240$). In addition, the $\delta^{18}\text{O}$ value of Tintigny plots centrally in the

272 field of eucrite analyses. The oxygen isotopic data is therefore consistent with

273 the classification of Tintigny as a eucrite.



274

275 **Figure 10:** Oxygen isotopic composition of Tintigny in comparison with HED
 276 data from Greenwood et al. (2017).

277

278 DISCUSSION AND CONCLUSIONS

279 In this work, we used petrography, mineralogy, and whole-rock major and
 280 trace-element chemistry to classify the Tintigny meteorite. In addition, we have
 281 undertaken oxygen isotope analysis which has confirmed that Tintigny is a
 282 member of the HED clan. Based on our studies we conclude that Tintigny is a
 283 non-cumulate eucrite, specifically a polymict basaltic eucrite.

284 Eucrites, together with howardites and diogenites, form the HED clan that
 285 constitutes 74.6% by number of all achondrites, and 3.6% by number of all
 286 meteorites in meteorite collections worldwide (Meteoritical Bulletin Database
 287 (<https://www.lpi.usra.edu/meteor/metbull.php>), accessed February 2021).

288 Based on the spectral data obtained in the laboratory and their comparison
289 with data measured by ground-based observatories and the results from the
290 NASA Dawn mission, HEDs are thought to originate from differentiated
291 asteroids with V-type spectra, and in particular 4-Vesta (McSween et al., 2010;
292 Moskowitz et al. 2010). Postcrystallization events on the parent body such as
293 thermal metamorphism, metasomatism, shock metamorphism, and space
294 weathering have led to the formation of rocks with complex geological histories
295 (Yamaguchi et al., 1994; Takeda et al., 1985; Warren et al., 2014). As
296 described earlier, Tintigny has also been affected by these processes, in
297 particular thermal and shock metamorphism and possibly metasomatism as
298 recorded in some grains (as Fe enrichment along veins and crystal rims).
299 Many HED meteorites are brecciated, with a general distinction between
300 monomict and polymict breccias (Delaney & Prinz, 1984; Mittlefehldt et al.,
301 2013, Zucolotto et al., 2018). These breccias result from large-scale impact
302 events of the Solar System bodies and witness to the importance of impact
303 processing of the surface and subsurface of planetary bodies. The lack of
304 chemical zoning in most minerals (except in some clasts), the presence of
305 Fe,Ni metal exsolutions in pyroxene, and sub-solidus exsolution of augite
306 lamellae within pigeonite hosts (Fig. 4) are indicative of parent body thermal
307 metamorphism (Righter & Drake, 1997; Vollmer et al., 2020). The formation of
308 clasts with symplectitic texture has been suggested to result from the
309 breakdown of metastable pyroxene in gabbroic eucrites (Patzner & McSween,
310 2012; Seddiki et al., 2013). Barrat et al. (2011) and Warren et al. (2014) linked

311 the formation of Fe enrichment along the veins and crystal rims to fluid-driven
312 alteration on the parent body surface.

313 Diogenites are mostly orthopyroxene cumulates that formed in plutons
314 which crystallized at varying levels within the crust. Eucrites are mostly basaltic
315 rocks that formed at faster cooling rates, most likely as a result of
316 emplacement either on the surface or at shallow depths. According to their
317 textural and compositional characteristics eucrites can be further divided into
318 basaltic rocks (mostly monomict breccias), cumulate gabbros, and polymict
319 eucrites made of different eucritic textures (without diogenitic clasts) like
320 Tintigny (Vollmer et al., 2020). Barrat et al. (2003) also divides them to
321 cumulate and noncumulate eucrites. Howardites formed as the products of
322 impact events on the parent body surface, occurring as breccias made from
323 different percentages of eucritic and diogenitic materials.

324 Meteoritical Bulletin Database (<https://www.lpi.usra.edu/meteor/metbull>;
325 August 2021) lists 2447 HED meteorites encompassing 1516 eucrites, 399
326 howardite, and 532 diogenites. Out of this number, only 69 of the HED are
327 *falls*, i.e., meteorites that have been observed falling and have been collected
328 soon after their impact, avoiding the detrimental effects of terrestrial
329 weathering, which are common in meteorite *finds* (meteorites without any fall
330 record) and even in some cases in *falls* if not collected immediately (Walker et
331 al., 2018; Pourkhorsandi, 2018; Pourkhorsandi et al., 2019). Including Tintigny,
332 only 39 eucrite falls are known to date, 11 of them occurred in Europe and
333 Tintigny being the only one from Belgium. This highlights the importance of

334 classification and accessibility of such a meteorite for further cosmochemical
335 and planetary studies and enriching our knowledge on the formation of HED
336 meteorites and their parent bodi(es). In addition to its scientific importance, we
337 emphasize the importance of the discovery of a historical meteorite fall in
338 bringing attention to national scientific heritage that has to be properly
339 understood and safeguarded for the generations of scientists, scholar, and
340 amateurs to come (Franza & Pratesi, 2021).

341

342 **Acknowledgments**

343 We all warmly thank the Schmitz family for their donation of the meteorite to
344 the RBINS. We thank W. Debouge, S. Cauchies, and J. de Jong for their
345 support in the clean labs and analysis facilities at the Laboratoire G-Time. We
346 appreciate constructive comments by the two anonymous reviewers and
347 editorial handing by Dr. A.P. Rossi.

348 This project has received funding from the European Union's Horizon 2020
349 research and innovation programme under the Marie Skłodowska-Curie grant
350 agreement No 801505. VD thanks the ERC StG "ISoSyC" and FRS-FNRS for
351 funding. SG, SD and VD thank the Brain-be Belspo projects BAMB and
352 DESIRED for funding.

353

354

355 **References**

- 356 Barrat J.A., Jambon A., Bohn M., Blichert-Toft J., Sautter V., Gopel C., Gillet
357 Ph. Boudouma O., and Keller F. 2003. Petrology and geochemistry of the
358 unbrecciated achondrite Northwest Africa 1240 (NWA 1240): An HED parent
359 body impact melt. *Geochimica et Cosmochimica Acta* 67:3959-3970.
- 360 Barrat J.A., Yamaguchi Y., Bunch T.E., Bohn M., Bollinger C., and Ceuleneer
361 G. 2011. Possible fluid-rock interactions on differentiated asteroids recorded in
362 eucritic meteorites. *Geochimica et Cosmochimica Acta* 75:3839-3852.
- 363 Franza A. and Pratesi G. 2021. Meteorites as a scientific heritage. *Conservar*
364 *Património* 36:106-121.
- 365 Gattacceca J., McCubbin F. M., Bouvier A., and Grossman J. 2020. The
366 meteoritical Bulletin No. 107. *Meteoritics & Planetary Science* 55:460-462.
- 367 Goodrich C. and Delaney J. 2000. Fe/Mg-Fe/Mn relations of meteorites and
368 primary heterogeneity of primitive achondrite parent bodies. *Geochimica et*
369 *Cosmochimica Acta* 64:149-160.
- 370 Greenwood R. C., Burbine T. H., Miller M. F., and Franchi I. A. 2017. Melting
371 and differentiation of early-formed asteroids: The perspective from high
372 precision oxygen isotope studies. *Chemie der Erde-Geochemistry* 77:1-43.
- 373 Kitts K. and Lodders K. 1998. Survey and evaluation of eucrite bulk
374 compositions. *Meteoritics & Planetary Science* 33:A197-A213.
- 375 McSween H.Y., Mittlefehldt D.W., Beck A.W., Mayne R.G., McCoy T.J. (2010)
376 HED Meteorites and Their Relationship to the Geology of Vesta and the Dawn

- 377 Mission. In: Russell C., Raymond C. (eds) The Dawn Mission to Minor Planets
378 4 Vesta and 1 Ceres. Springer, New York, NY
- 379 Miller M. F., Franchi I. A., Sexton A. S., and Pillinger C. T. 1999. High precision
380 $\Delta^{17}\text{O}$ isotope measurements of oxygen from silicates and other oxides:
381 Methods and applications. *Rapid Communications in Mass Spectrometry*
382 13:1211-1217.
- 383 Miller M. F. 2002. Isotopic fractionation and the quantification of ^{17}O anomalies
384 in the oxygen three-isotope system: an appraisal and geochemical
385 significance. *Geochimica et Cosmochimica Acta* 66:1881-1889.
- 386 Mittlefehldt D. W., Herrin J. S., Quinn J. E., Mertzman S. A., Cartwright J. A.,
387 Mertzman K. R., and Peng Z. X. 2013. Composition and petrology of HED
388 polymict breccias: The regolith of (4) Vesta. *Meteoritics & Planetary Science*
389 48:2105-2134.
- 390 Mittlefehldt D. W. 2015. Asteroid (4) Vesta: I. The howardite-eucrite-diogenite
391 (HED) clan of meteorites. *Chemie der Erde - Geochemistry* 75:155-183.
- 392 Marshall D. 1996. Ternplot: An excel spreadsheet for ternary diagrams.
393 *Computers & Geoscience* 22:697-699.
- 394 Morimoto N. 1988. Nomenclature of pyroxenes. *Mineralogy and Petrology*
395 39:55-76.
- 396 Moskovitz N. A., Willman M., Burbine T. H., Binzel R., P., and Bus S. J. 2010.
397 A spectroscopic comparison of HED meteorites and V-type asteroids in the
398 inner Main Belt. *Icarus* 208:773-788.

- 399 Papike J.J., Karner J.M., and Shearer C.K. 2003. Determination of planetary
400 basalt parentage: A simple technique using the electron microprobe. *American*
401 *Mineralogist* 88:469-472. Patzer A. and McSween H. Y. 2012. Ordinary
402 (mesostasis) and not-so-ordinary (symplectites) late-stage assemblages in
403 howardites. *Meteoritics & Planetary Science* 47:1475-1490.
- 404 Pourkhorsandi H. 2018. Meteorites of Iran and hot deserts: classification and
405 weathering. PhD Thesis, Aix-Marseille Université.
- 406 Pourkhorsandi H., Gattacceca J., Rochette P., D'Orazio M., Kamali H., de
407 Avillez R., Letichevsky S., Djamali M., Mirnejad H., Debaille, and Jull A. J. T.
408 2019. Meteorites from the Lut Desert (Iran). *Meteoritics & Planetary Science*
409 54:1737-1763.
- 410 Righter K. and Drake M. J. 1997. A magma ocean on Vesta: Core formation
411 and petrogenesis of eucrites and diogenites. *Meteoritics & Planetary Science*
412 32:929-944.
- 413 Seddiki A., Moine B., Cottin J. Y., Bascou J., Godard M., Faure F., Bourot-
414 Denise M., and Remaci N. 2013. A mineralogical and geochemical study of
415 polymict eucrite discovered in Sahara of southwest Algeria. *Arabian Journal of*
416 *Geosciences* 6:3175-3184.
- 417 Starkey N. A., Jackson C. R. M., Greenwood R. C., Parman S., Franchi I. A.,
418 Jackson M., Fitton J. G., Stuart F.M., Kurz M., and Larsen L. M., 2016. Triple
419 oxygen isotopic composition of the high $^3\text{He}/^4\text{He}$ mantle. *Geochimica et*
420 *Cosmochimica Acta* 176:227-238.

- 421 Takeda H. and Mori H. 1985. The polymict eucrites. 1985. The diogenite-
422 eucrite links and the crystallization history of a crust of their parent body.
423 *Journal of Geophysical Research* 90:C636-C648.
- 424 Vollmer C., Rombeck S., Roszjar J., Sarafian A. R., and Klemme S. 2020. The
425 brecciated texture of polymict eucrites: Petrographic investigations of
426 unequilibrated meteorites from the Antarctic Yamato collection. *Meteoritics &*
427 *Planetary Science* 55:558-574.
- 428 Walker R., Yin Q., and Heck P. 2018. Rapid effects of terrestrial alteration on
429 highly siderophile elements in the Sutter's Mill meteorite. *Meteoritics &*
430 *Planetary Science* 53:1500-1506.
- 431 Warren P. H., Rubin A. E., Isa J., Gessler N., Ahn I., and Choi B. 2014.
432 Northwest Africa 5738: Multistage alteration in an extraordinarily evolved
433 eucrite. *Geochimica et Cosmochimica Acta* 141:199-227.
- 434 Wasson J. and Kallemeyn G. 1988. Compositions of chondrites. *Philosophical*
435 *Transactions of the Royal Society A: Mathematical, Physical and Engineering*
436 *Sciences* 325:535-544.
- 437 Yamaguchi A., Takeda H., Bogard D. D., and Garrison D. 1994. Textural
438 variations and impact history of the Millbillillie eucrite. *Meteoritics* 29:237-245.
- 439 Zucolotto M. E., Tosi A. A., Villaca C. V.N., Moutinho A. L.R., Andrade D. P.P.,
440 Faulstich F., Gomes A. M.S., Rios D. C., Rocha M. C. 2019. Serra Pelada: the
441 first Amazonian meteorite fall is a Eucrite (basalt) from asteroid 4-Vesta. *Anais*
442 *da Academia Brasileira de Ciências* 90:3-16.

443 **Tables:**

444 Table 1: The analyzed pyroxene and plagioclase compositions (in wt%) from Tintigny.

Mineral	Pyx	Pyx	Pyx	Pyx	Pyx	Pyx	Pyx	Pyx	Pyx	Pyx	Pyx	Pyx	Pyx	Pyx	Plg	Plg	Plg	Plg
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#1	#2	#3	#4
SiO₂	52.57	52.53	52.64	49.91	51.26	49.09	51.03	49.27	49.81	53.01	46.09	47.68	49.81	45.54	47.20	48.20	45.55	50.14
Al₂O₃	1.70	0.61	0.83	0.59	0.82	0.68	0.94	1.24	0.81	1.15	1.98	0.97	1.04	1.17	32.25	33.23	34.16	31.01
TiO₂	0.26	0.15	0.11	0.39	0.51	0.42	0.20	0.47	0.71	0.15	1.11	0.74	0.67	0.92	0.00	0.00	0.01	0.03
FeO	20.87	27.24	23.95	32.26	17.91	32.54	23.61	27.97	28.50	20.46	32.58	31.56	23.21	37.84	0.63	0.57	0.51	0.63
Cr₂O₃	0.84	0.22	0.61	0.23	0.31	0.30	0.93	0.41	0.35	0.74	0.24	0.21	0.33	0.18	b.d.l.	b.d.l.	0.01	b.d.l.
MnO	0.76	0.74	0.86	1.06	0.45	0.91	0.85	0.88	0.88	0.74	0.87	0.82	0.75	1.03	b.d.l.	0.02	0.01	0.05
MgO	19.40	17.28	17.69	10.33	10.51	12.96	17.50	10.72	11.49	20.84	5.37	7.88	8.77	2.58	0.06	0.02	0.05	0.04
CaO	3.98	1.21	3.69	4.85	17.80	1.55	4.44	7.52	7.00	2.80	9.63	8.15	15.25	9.08	17.00	16.83	17.99	14.65
Na₂O	0.02	0.03	0.01	0.01	0.04	b.d.l.	0.01	0.07	0.07	b.d.l.	0.17	0.10	0.05	0.01	1.52	1.64	1.06	2.48

K₂O	b.d.l.	0.03	0.02	0.01	0.01	0.01	b.d.l.	0.02	0.02	0.01	0.01	0.05	0.01	b.d.l.	0.08	0.10	0.02	0.15
NiO	0.05	0.06	0.03	0.03	0.07	0.15	b.d.l.	0.08	0.03	0.01	0.04	b.d.l.	0.07	0.07	0.01	0.01	b.d.l.	0.05
Total	100.4 0	100.1 0	100.4 4	99.67	99.69	98.61	99.51	98.65	99.67	99.91	98.09	98.16	99.96	98.42	98.75	100.6 2	99.37	99.23
En (mol%)	57.1	51.7	52.4	32.4	31.5	40.1	51.6	33.7	35.3	60.7	17.6	25.1	26.8	8.5	-	-	-	-
Fs (mol%)	34.5	45.7	39.8	56.7	30.1	56.5	39.0	49.3	49.2	33.4	59.8	56.3	39.8	70.0	-	-	-	-
Wo (mol%)	8.4	2.6	7.9	10.9	38.4	3.4	9.4	17.0	15.5	5.9	22.6	18.6	33.5	21.5	-	-	-	-
Fe/Mn	27.1	36.3	27.5	30.1	39.3	35.3	27.4	31.4	32.0	27.3	37.0	38.0	30.6	36.3	-	-	-	-
Fe/Mg	0.6	0.9	0.8	1.7	1.0	1.4	0.8	1.5	1.4	0.6	3.4	2.2	1.5	8.2	-	-	-	-
An (mol%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	85.7	84.5	90.3	75.8
Ab (mol%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	13.8	14.9	9.6	23.2
Or (mol%)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.5	0.6	0.1	0.9

446

447

448

449

Journal Pre-proof

450 Table 2: Major and trace element composition of Tintigny eucrite.
 451 Concentrations are reported in mg/g and $\mu\text{g/g}$ for major and trace elements,
 452 respectively.

	Tintigny	RSD (%)	BHVO-2¹	RSD (%)	BVHO-2²
Na	3.26	2	16.0	0.7	16.4
Mg	46.1	1	43.5	2	43.6
Al	63.0	0.8	71.7	0.5	71.6
Si	229	1	235	0.4	233
P	0.206	1	1.17	2	1.2
K	0.339	0.6	4.29	0.8	4.30
Ca	68.3	0.7	81.3	1	81.7
Ti	3.78	1	16.4	1	16.3
Cr	2.73	0.4	0.315	1	0.280
Mn	4.21	1	1.33	1	1.3
Fe	142.3	1	89.1	0.4	86.3
Ga	2.63	12	22.57	1	21.7
Rb	0.351	49	8.35	5	9.80
Sr	79.7	1	394	1	389
Y	19.0	1	25.2	0.4	28.0
Zr	49.6	1	162	1	172
Nb	4.34	2	17.2	1	18
Ba	34.4	2	134	1	130
La	4.65	3	16.0	1	15.2
Ce	10.5	0	37.6	1	38.0
Pr	1.51	4	5.25	2	5.34
Nd	7.04	3	24.1	3	25.0

Sm	2.09	5	6.18	4	6.20
Eu	0.660	2	2.10	2	2.07
Gd	2.91	2	6.40	3	6.30
Tb	0.490	2	0.910	1	0.940
Dy	3.32	2	5.34	2	5.31
Ho	0.727	1	0.994	3	1.04
Er	2.08	4	2.52	4	2.54
Tm	0.310	3	0.337	8	0.335
Yb	1.99	3	2.00	2	2.00
Lu	0.280	11	0.274	7	0.280
Hf	1.39	2	4.32	4	4.47
Ta	0.270	10	1.22	2	1.40
Th	0.441	6	1.17	2	1.25
U	0.121	3	0.407	5	0.412
Pb	0.162	17	0.769	1	1.65

453 ¹: BHVO-2 basalt reference material analyzed during same session. ²:

454 ²Compilled literature value from GeoReM database ([http://georem.mpch-](http://georem.mpch-mainz.gwdg.de/)
 455 [mainz.gwdg.de/](http://georem.mpch-mainz.gwdg.de/))

456

Highlights

- Tintigny meteorite fell in February 1971 in a village in southern Belgium.
- Based on our multimethod study, we classified it as a polymict eucrite.
- This type of meteorites are achondrites from howardite-eucrite-diogenite (HED) clan.
- HED meteorites are believed to originate from the surface of the asteroid 4-Vesta.
- Tintigny is one of the 39 eucrite falls known to date.

AUTHORSHIP STATEMENT

Manuscript title: Tintigny meteorite: the first Belgian achondrite

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the Planetary and Space Science journal.

Competing interests

The authors declare no competing interests.

Journal Pre-proof