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# ON THE ORIGIN OF METALLIC IRON IN EUCRITE BRECCIAS: EFFECTS OF IMPACT SHOCK AND MIXING ON THE SURFACE OF (4) VESTA.

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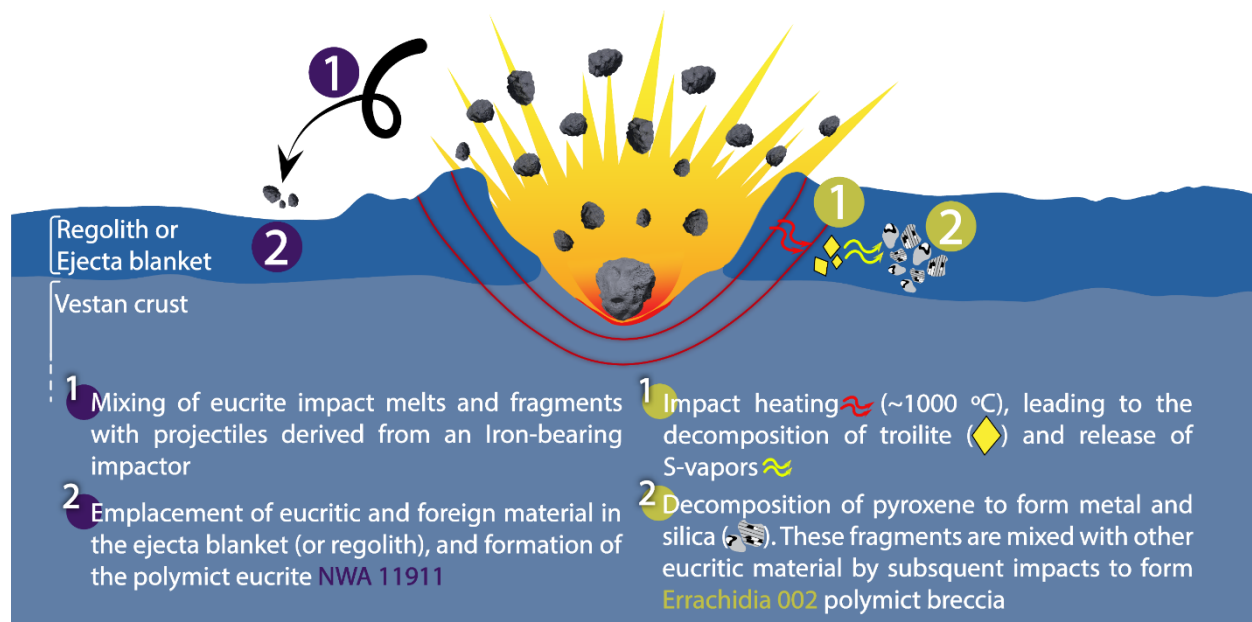
## ABSTRACT

Eucrites provide important insights on the formation and the evolution of the surface and the crust of their parent body, widely believed to be the asteroid (4) Vesta. Among their minor components is metallic iron, which is not fairly described in the literature and whose formation mechanisms remain poorly understood. We performed scanning electron microscopy (SEM) and electron microprobe analysis (EPMA) investigations on the eucritic samples Errachidia 002 and Northwest Africa (NWA) 11911, with more focus on metallic iron disseminated in them, in order to constrain the processes involved in its formation, and its implications for their parent body collisional history. Errachidia 002 is a polymict eucrite that consists of basaltic and noritic (diogenite) clasts set in a fragmental matrix. Fe-metals in this meteorite contain <0.04 wt% Ni, and 0.05 wt% Co, and they are mostly associated with silica in pyroxene. This suggests their formation by decomposition of troilite, which generated S-vapors that subsequently reacted with FeO in pyroxene during an impact event, producing pure Fe-metal and silica. NWA 11911 is also a polymict eucrite composed mainly of unequilibrated and equilibrated eucritic clasts set in a clastic groundmass. Metallic iron in this breccia is either enclosed in the fragmental matrix, or within a vitrophyric impact melt clast. Its Ni and Co contents are ~2.8 and 0.6 wt%, respectively, implying a contamination by projectiles derived from an iron-bearing impactor. Our results point

out the major role impacts played in controlling the surface features and mineral compositions of early formed bodies in the solar system such as (4) Vesta.

**Keywords:** eucrite, (4) Vesta, impact processes, secondary alteration.

## GRAPHICAL ABSTRACT



## 1. INTRODUCTION

Howardites, eucrites and diogenites (HEDs) are among the oldest igneous rocks in the solar system, and the most represented group of achondrite meteorites recovered from the surface of Earth (Roszjar et al., 2016; Hublet et al., 2017; Kleine and Wadhwa, 2017). Eucrites are either basaltic or cumulate rocks, respectively formed within the upper and lower crust of their parent body (Mittlefehldt, 2015). Diogenites are ultramafic (orthopyroxenitic, harzburgitic, dunitic, or noritic) rocks formed as plutons intruding the eucritic crust (Barrat et al., 2010; Beck and McSween, 2010; Yamaguchi et al., 2011). Howardites are rocks containing both eucrite and diogenite debris, as well as exogenous material (Duke and Silver, 1967; Lorenz et al., 2007; Unsalan et al., 2019; Jenniskens et al., 2021). These meteorites are believed to have originated from the asteroid (4) Vesta and its collisional family (i.e., vestoids), based on spectroscopic evidence from telescopic observations and Dawn spacecraft data (Binzel and Xu, 1993; Burbine et al., 2001; De Sanctis et al., 2013; McSween et al., 2013).

Eucrites record a wide array of post-crystallization processes such as widespread crustal metamorphism (Takeda and Graham, 1991; Yamaguchi et al., 1996; Yamaguchi et al., 2009; Shisseh et al., 2022), brecciation and impact mixing (Metzler et al., 1995; Kennedy et al., 2019), and various types of secondary alterations driven by S-rich or aqueous agents (Barrat et al., 2011; Zhang et al., 2013; Warren et al., 2014; Shisseh et al., 2023). Among the minor phases found in eucrites is iron metal (Duke, 1965; Mayne et al., 2009). Previous studies suggested that it formed during magmatic crystallization at reduced conditions (Duke, 1965), or by post-crystallization processes such as thermal metamorphism, contamination by iron-bearing projectiles, reduction of troilite and pyroxene during impact events, dissociation reaction of  $\text{Fe}^{2+}$  in pyroxene, deposition from a FeO-rich fluid, or by troilite alteration by  $\text{H}_2\text{O}$ -rich fluids (Duke, 1965; Palme et al., 1988; Lorenz et al., 2007; Warren et al., 2014; Guo et al., 2021).

In this paper, we explore the petrology and the mineralogy of the eucrite breccias Errachidia 002 and NWA 11911, in order to unravel their formation history. We also examine the textures and the compositions of metallic irons found in both rocks, for the purpose of identifying their origin and implication for the post-magmatic history of the HED parent body.

## 2. METHODS

A 4.02 g piece of the polymict eucrite Errachidia 002 was recovered during a systematic prospecting mission to recover meteorites in the region of Errachidia in Morocco, in October 2017. A piece of NWA 11911 (8.9 g) was provided by Luc Labenne for classification at the Institut de minéralogie, de physique des matériaux et de cosmochimie (IMPMC), Muséum national d'Histoire naturelle (MNHN) of Paris, France. Backscattered electron (BSE) images were obtained using the scanning electron microscope TESCAN VEGAII LSU, at IMPMC (MNHN of Paris, France). X-ray elemental maps were obtained using the same system. Additional BSE images were acquired using FEI Quanta 450 ESEM FEG equipped with microanalytical energy dispersive system (EDS) Bruker QUANTAX XFlash Detector 6-10, at the Centro per la Integrazione della Strumentazione dell'University of Pisa (CISUP, Italy). Images were acquired in backscattered electron mode at an accelerating voltage of 15 kV.

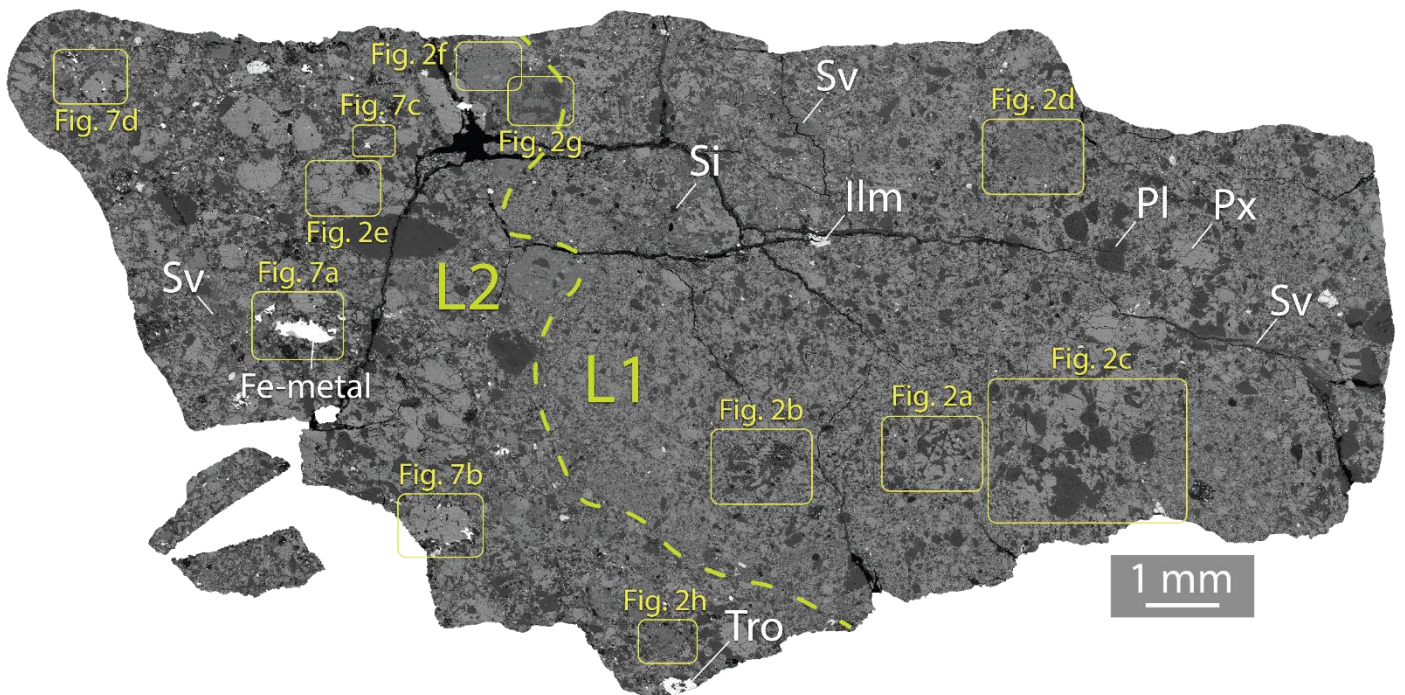
The composition of the minerals was obtained using a CAMECA SX-FIVE EPMA at ITeP (Sorbonne University in Paris, France), at an accelerating voltage of 15 kV and a beam current of 10 nA. Further analyses were performed using the JEOL 8200 Super Probe at the Institute of

Meteoritics (University of New Mexico in Albuquerque, USA). Mineral standards are: orthoclase (Al, K), apatite (P), pyrite (Fe), Cr<sub>2</sub>O<sub>3</sub> (Cr), albite (Na), diopside (Mg, Si, Ca) and MnTiO<sub>3</sub> (Ti, Mn). The detection limits for Fe-metal analysis are: 0.04 wt % for Ni, 0.03 wt% for Fe and Co, 0.02 wt% for P, and 0.01 wt% for S.

### 3. PETROGRAPHY AND MINERAL COMPOSITION

#### 3.1. ERRACHIDIA 002

Errachidia 002 consists predominately of clasts derived from various lithologies embedded in a fragmental groundmass (Fig. 1; Table 1). A backscattered electron (BSE) mosaic map of the polished section studied allowed the distinction between two lithologies (L1 and L2), separated by a network of shock veins up to 200 µm in width (see the BSE mosaic map in Fig. 1).



**Fig. 1.** Backscattered electron mosaic map of Errachidia 002. The dashed green line shows the limit between two lithologies; lithology 1 (L1) and lithology 2 (L2). Px = pyroxene; Pl = plagioclase; Ilm = ilmenite; Si = silica; Mx = matrix; L = lithology; Sv = shock vein.

1 **3.1.1. Lithology 1 (L1)**

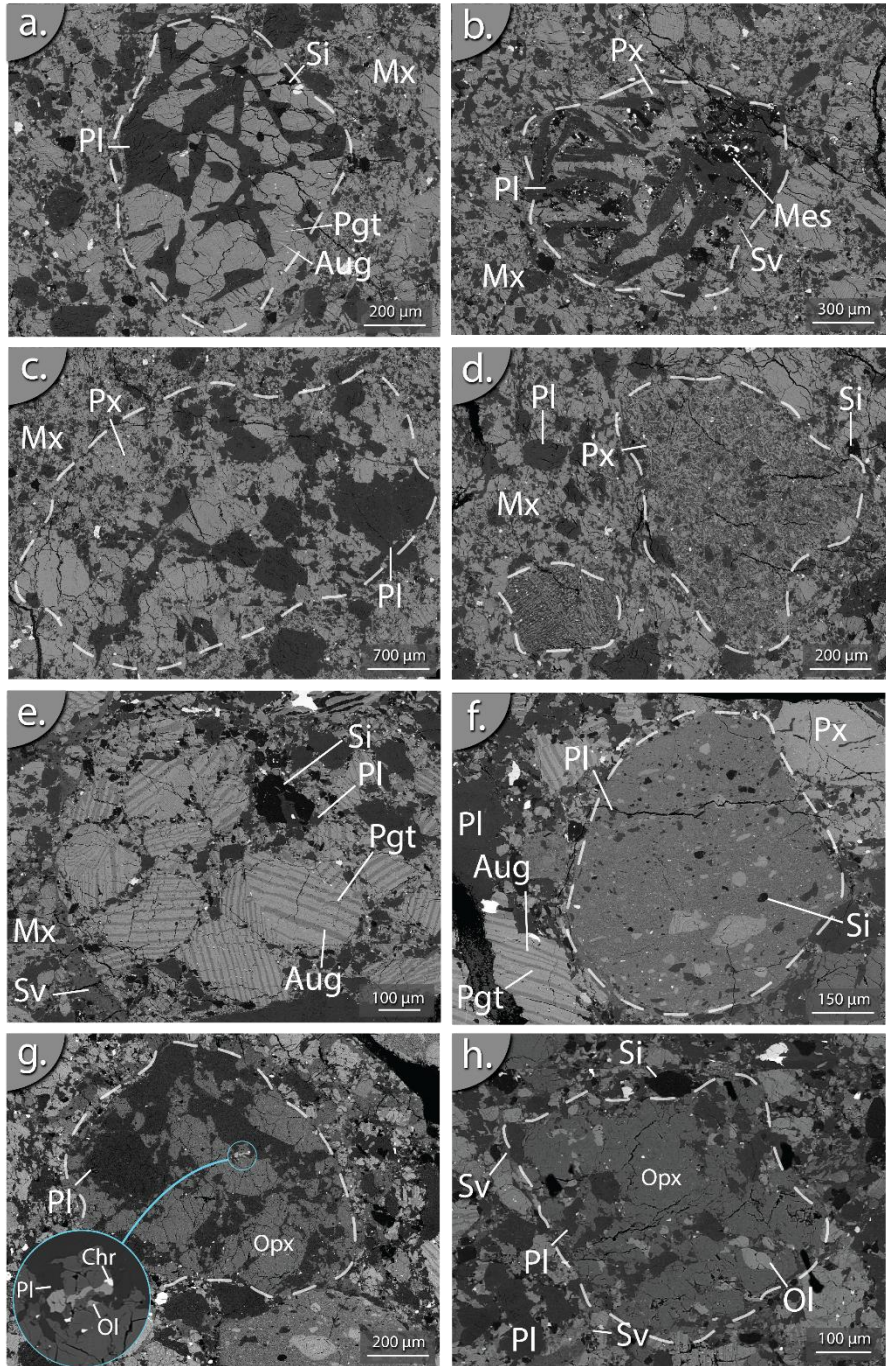
2 The first area (L1) is composed of a fragmental and locally recrystallized clastic matrix  
3 embedding subrounded to rounded basaltic, equigranular, and fine-grained clasts ranging from  
4 0.6 to 3 mm in size (Fig. 2). The basaltic clast shown in Fig. 2a exhibits a subophitic texture, and  
5 consists of pigeonite with 5- $\mu$ m-thick exsolution lamellae of augite, lath-shaped plagioclase with  
6 inclusions of pyroxene and troilite following crystallographic directions, and silica surrounded  
7 by radial cracks. The subophitic clast in Fig. 2b consists of pyroxene and plagioclase laths, as  
8 well as abundant mesostasis (silica, troilite, and ilmenite), and a few glassy shock veins with a  
9 thickness up to 20  $\mu$ m intruding its margins. The clast shown in Fig. 2c is 3 mm across, which  
10 makes it the largest clast identified in L1. It has an equigranular texture overall with no  
11 mesostasis domains, and contains pyroxene and plagioclase up to 0.7 mm in diameter. We have  
12 also identified clasts composed predominately of elongated skeletal low-Ca pyroxene (60  $\mu$ m in  
13 length) with random orientations, and anhedral pyroxene and plagioclase fragments, set in a fine-  
14 grained groundmass consisting of 5- $\mu$ m-sized high-Ca pyroxene, plagioclase, and minor opaques  
15 (Fig. 2d).

16 **3.1.2. Lithology 2 (L2)**

17 The second portion (L2) consists of a clastic matrix embedding basaltic, glassy, and Mg-rich  
18 diagenetic fragments. Pyroxene in the basaltic clasts is equilibrated with 25- $\mu$ m-thick exsolution  
19 lamellae of augite that are mostly faulted or bended (Fig. 2e). Other phases in these clasts include  
20 plagioclase and silica (Fig. 2e). The glassy clasts are composed of mineral fragments (pyroxene,  
21 plagioclase, and silica) set in a glassy or devitrified groundmass (Fig. 2f). We found also  
22 fragments consisting mainly of BSE-dark Mg-rich pyroxene with various proportions of  
23 plagioclase and olivine (Fig. 2g, h). The matrix is crosscut by numerous glassy shock veins up to  
24 300  $\mu$ m in width, containing entrained fragments of pyroxene, plagioclase, and silica with  
25 rounded margins (Fig. 1; Fig. 2e).

26



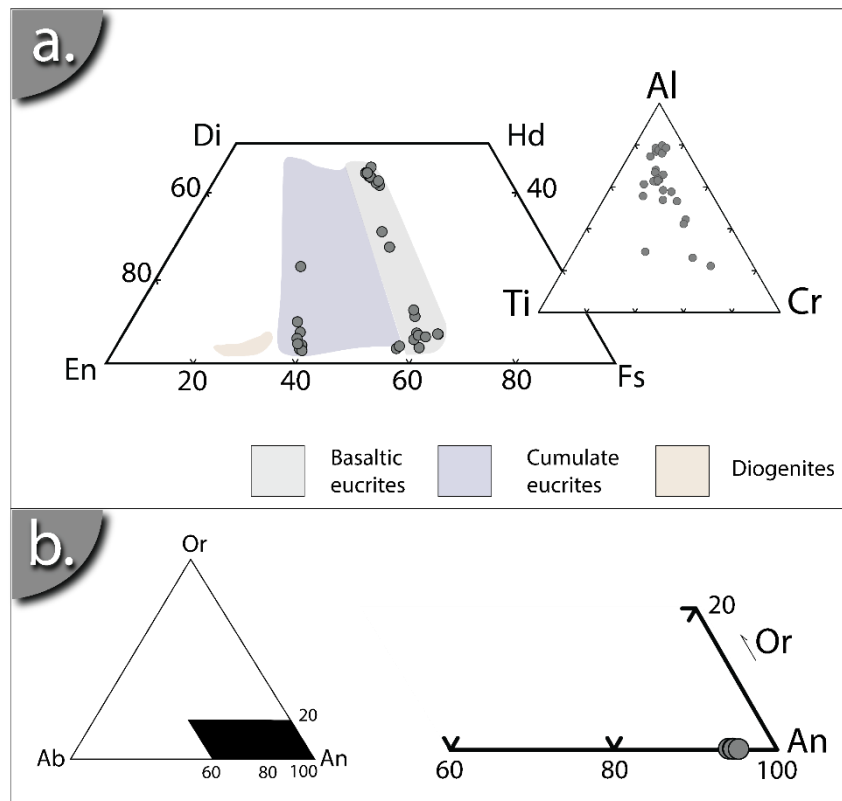


27

28 **Fig. 2.** Backscattered electron images of eucritic, glassy, and noritic diogenite clasts found in Errachidia  
 29 002 in lithologies 1 (a-d) and 2 (e-h). (a) subophitic basaltic clast. (b) fine-grained subophitic clast.  
 30 Mesostasis consists of silica, troilite, and ilmenite. (c) medium-grained, equigranular eucritic clast. (d)  
 31 fine-grained clast with elongated pyroxene and rounded pyroxene and plagioclase fragments set in a fine-  
 32 grained matrix consisting of the same mineral phases. (e) clasts with equilibrated pyroxene (with host  
 33 pigeonite and exsolution lamellae of augite) crystals (f) rounded glassy clast containing pyroxene and  
 34 silica fragments. (g, h) noritic diogenite clasts composed of Mg-rich pyroxene, plagioclase, and Mg-rich  
 35 olivine. Px = pyroxene; Pgt = pigeonite; Aug = augite; Ol = olivine; Pl = plagioclase; Si = silica; Chr =  
 36 chromite; Mes = mesostasis; Sv = shock vein.

37 **3.1.3. Mineral composition**

38 The EPMA results and endmember compositions of pyroxene and plagioclase in Errachidia  
 39 002 are given in Table 1, and are plotted in Fig. 3a, b. In L1, the compositions of host pigeonite  
 40 in the subophitic clasts in Fig. 2a and Fig. 2b range from  $\text{En}_{32}\text{Fs}_{62}\text{Wo}_6$  ( $\text{Mg}\# = [\text{Mg}/(\text{Mg} +$   
 41  $\text{Fe})] * 100 = 35$ ) to  $\text{En}_{35}\text{Fs}_{54}\text{Wo}_{11}$  ( $\text{Mg}\# = 39$ ). The clast exhibiting the equigranular texture (Fig.  
 42 2c) consists of more magnesian pyroxene, with a composition of  $\text{En}_{42}\text{Fs}_{55}\text{Wo}_3$  ( $\text{Mg}\# = 43$ ). The  
 43 host pigeonite found in L2 (Fig. 2e) has a composition of  $\text{En}_{35}\text{Fs}_{60}\text{Wo}_5$  ( $\text{Mg}\# = 37$ ), and the  
 44 exsolved augite has a composition of  $\text{En}_{30}\text{Fs}_{28}\text{Wo}_{42}$ . The clasts shown in Fig. 2g and Fig. 2h have  
 45 pyroxene with the most Mg-rich compositions in the meteorite ( $\text{En}_{59-61}\text{Wo}_2$ ;  $\text{Mg}\# 64$ ), as well as  
 46 plagioclase with a composition of  $\sim\text{An}_{95}$ , and olivine with homogenous compositions of  $\text{Fo}_{51-52}$ .  
 47 Analyzed plagioclase grains in both lithologies have a composition of  $\text{An}_{93-95}$  (Fig. 3b). The  
 48 glassy material in the shock veins contains 14 wt%  $\text{Al}_2\text{O}_3$ , 0.88 wt%  $\text{TiO}_2$ , 0.44 wt%  $\text{Na}_2\text{O}$ , and  
 49 10.8 wt%  $\text{CaO}$ .



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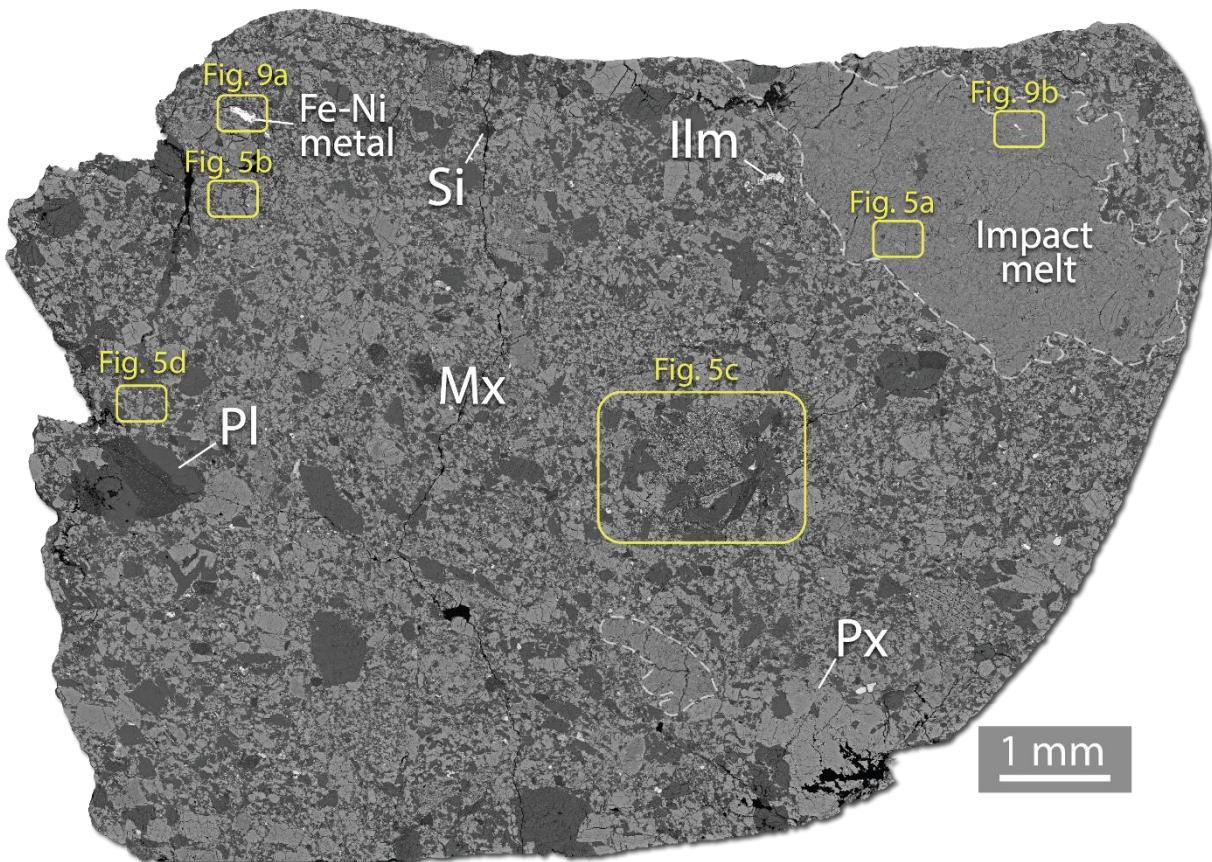
51 **Fig. 3.** Pyroxene (a) and plagioclase (b) endmember compositions in Errachidia 002. Compositional fields  
 52 of basaltic eucrites, cumulate eucrites and diogenites are from Yamaguchi et al. (2017).

53



## 55 3.2.1. Petrographic characteristics

56 The main petrographic and geochemical characteristics of this meteorite are described in  
 57 Shisseh et al. (2023). This meteorite is a polymict eucrite, as it consists of basaltic eucrite debris  
 58 composed of pyroxene displaying unequilibrated and equilibrated major (Fe, Mg) and minor (Cr,  
 59 Ti, Al) element compositions. The matrix of NWA 11911 contains glassy shock veins up to 80  
 60  $\mu\text{m}$  in thickness embedding rounded and subrounded fragments of pyroxene, plagioclase, and  
 61 silica (Fig. 5a), as well as vitrophyric impact melt clasts 1 to 5 mm across at their largest point,  
 62 containing mainly skeletal and fan spherulitic pyroxenes set in a glassy groundmass (Fig. 4, Fig.  
 63 5b). The main minerals in the matrix and the clasts in NWA 11911 are pyroxene and plagioclase,  
 64 with minor silica, chromite, ulvöspinel, ilmenite, troilite, ferroan olivine, and accessory Fe-Ni  
 65 metal (Fig. 4).

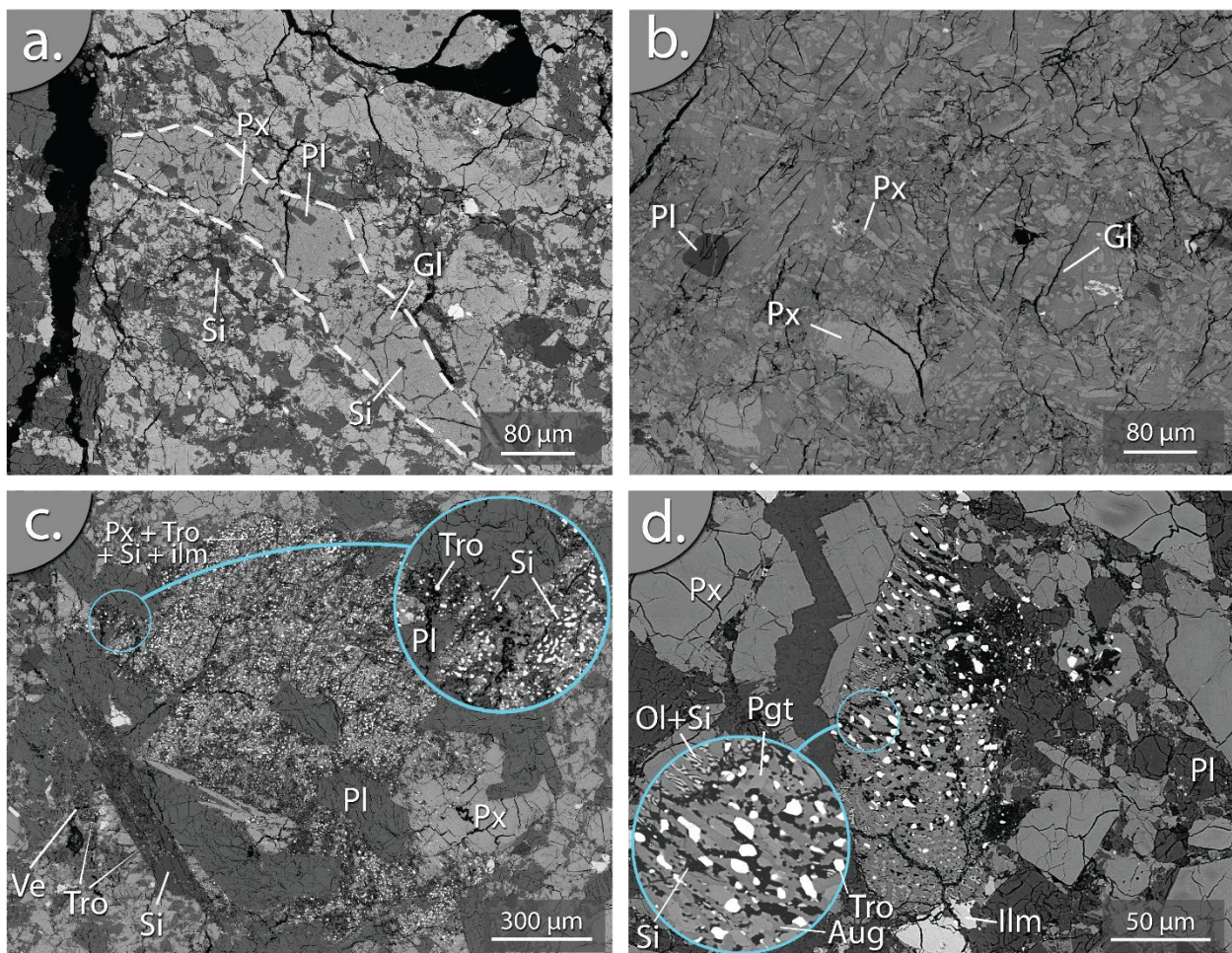


66

67 **Fig. 4.** Backscattered electron mosaic map of NWA 11911. Dashed white lines show the location of  
 68 impact melt clasts embedded in the matrix. Px = pyroxene; Pl = plagioclase; Ilm = ilmenite; Si = silica;  
 69 Mx = matrix.



70 In a recent work, we showed that NWA 11911 contains evidence of secondary alteration  
 71 involving aqueous fluids, in the form of Fe-enrichment along the fractures in pyroxene, and  
 72 veinlets of fayalite associated with Ca-rich secondary plagioclase, Cr-spinel, troilite, and apatite  
 73 (Shisseh et al., 2023). We report the presence of two further clasts with different textures and  
 74 mineralogies than the remaining eucritic clasts embedded in the matrix. The first clast, shown in  
 75 [Fig. 5c](#), is up to 1.5 mm in size and exhibits an ophitic to subophitic texture. It is mainly  
 76 composed of pyroxene, plagioclase, lath-shaped silica, and ilmenite. Our observations show that  
 77 most of pyroxene in this clast is replaced with a fine-grained assemblage of secondary low-Ca  
 78 pyroxene, high-Ca pyroxene, silica, troilite, ilmenite with sizes ranging from 6 to 11  $\mu\text{m}$ .  
 79 Primary silica in the clast is porous, and contains fine troilite inclusions scattered throughout.  
 80 The margins of some plagioclase grains are also invaded by these inclusions. The second clast  
 81 exhibits a symplectite texture, and contains two phases of pyroxene (pigeonite and augite) with a  
 82 size of 7  $\mu\text{m}$ , troilite, and an intergrowth of olivine and silica ([Fig. 5d](#)).

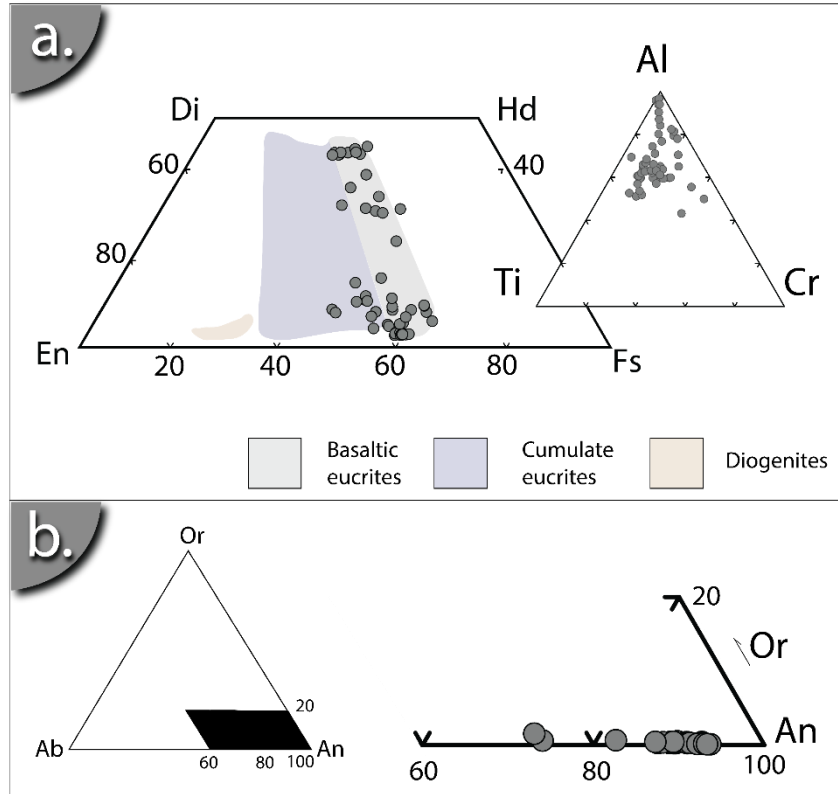


84 **Fig. 5.** Backscattered electron images impact products and clasts exhibiting replacement and symplectic  
85 textures in NWA 11911. (a) glassy shock vein containing entrained fragments of pyroxene, plagioclase,  
86 and silica. (b) close-up view of the impact melt clast in NWA 11911 (see upper right clast marked by  
87 dashed white line in Fig. 4). The glassy groundmass contains zoned pyroxene microlites and digested  
88 mineral fragments. (c) a subophitic clast predominately composed of pyroxene, plagioclase and lathy  
89 silica. Relict pyroxene (lower right of the image) is replaced by a fine-grained assemblage of augite,  
90 pigeonite, troilite, and silica with minor ilmenite. (d) Symplectic clast composed of vermicules and  
91 exsolutions of olivine and silica, as well as troilite and two phases of pyroxene (augite and pigeonite). Px  
92 = pyroxene; Pgt = pigeonite; Aug = augite; Ol = olivine; Pl = plagioclase; Si = silica; Tro = troilite; Ilm =  
93 ilmenite; Gl = glass; Ve = vesicle.

### 94 3.2.2. Mineral composition

95 The average composition ( $\pm 1$  standard deviation) of low-Ca pyroxene in NWA 11911 is  
96  $\text{En}_{39\pm 4}\text{Fs}_{54\pm 7}\text{Wo}_{7\pm 6.7}$  ( $n = 39$ ), and of high-Ca pyroxene is  $\text{En}_{29\pm 2.2}\text{Fs}_{35\pm 7}\text{Wo}_{36\pm 6.4}$  (Table 1; Fig. 6a).  
97 Plagioclase has a range of compositions of  $\text{An}_{72-93}\text{Ab}_{6-26}\text{Or}_{1-2}$  (Table 1; Fig. 6b). The pyroxene  
98 and plagioclase grains entrained in the shock vein shown in Fig. 5a are  $\text{En}_{37-39}\text{Fs}_{49-59}\text{Wo}_{2-14}$   
99 ( $\text{Fe}/\text{Mn} = 31$ ), and  $\text{An}_{90-93}\text{Ab}_{5-7}$ , respectively. The glass in the shock veins contains 13, 0.7, 11,  
100 0.2 wt% of  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ , CaO, and  $\text{Na}_2\text{O}$ , respectively. Zoned pyroxene microlites in the impact  
101 melt clast in Fig. 5b display compositional ranges of  $\text{En}_{42-49}\text{Fs}_{44-49}\text{Wo}_{7-9}$ . In average, The  $\text{Al}_2\text{O}_3$ ,  
102  $\text{TiO}_2$  CaO  $\text{Na}_2\text{O}$  contents of the glassy groundmass are 13.8, 0.6, 10.5, and 0.16 wt%. The relict  
103 pyroxene and the plagioclase in the clast shown in Fig. 5c have endmember compositions of  
104  $\text{En}_{33}\text{Fs}_{58}\text{Wo}_9$  ( $\text{Mg}\# = 0.36$ ;  $\text{Fe}/\text{Mn} = 32$ ), and  $\text{An}_{75-83}$  with FeO content of 0.3-0.7 wt%,  
105 respectively. The secondary phases in the pyroxene portions displaying replacement textures are  
106 augite ( $\text{En}_{26-28.6}\text{Fs}_{27.9-31}\text{Wo}_{43-43.5}$  ( $\text{Mg}\# = 0.46-0.51$ ;  $\text{Fe}/\text{Mn} = 39-42$ ), pigeonite ( $\text{En}_{23.8-26.6}\text{Fs}_{43.6-}$   
107  $48\text{Wo}_{28.2-29.8}$  ( $\text{Mg}\# = 0.33-0.37$ ;  $\text{Fe}/\text{Mn} = 32-34$ ), silica (96 wt%  $\text{SiO}_2$ ) that contains 1.2 wt% FeO,  
108 ilmenite with 52 wt%  $\text{TiO}_2$  and 44.6 wt% FeO, and troilite (36 wt% S; Table 1). Olivine in the  
109 symplectic assemblage in Fig. 5d is FeO-rich ( $\text{Fa}_{81}$ ); augite is  $\text{En}_{28.1}\text{Fs}_{28.4}\text{Wo}_{43.5}$  ( $\text{Mg}\# = 0.49$ ),  
110 and; pigeonite is  $\text{En}_{33.7-35.9}\text{Fs}_{61.7-63.4}\text{Wo}_{2.4-2.9}$  ( $\text{Mg}\# = 0.33-0.37$ ). Silica associated with these  
111 phases contains 96 wt%  $\text{SiO}_2$ , and up to 1.2 wt% FeO (Table 1).

112



113

114 **Fig. 6.** Pyroxene (a) and plagioclase (b) endmember compositions in NWA 11911. Compositional fields  
 115 of basaltic eucrites, cumulate eucrites and diogenites are from Yamaguchi et al. (2017).

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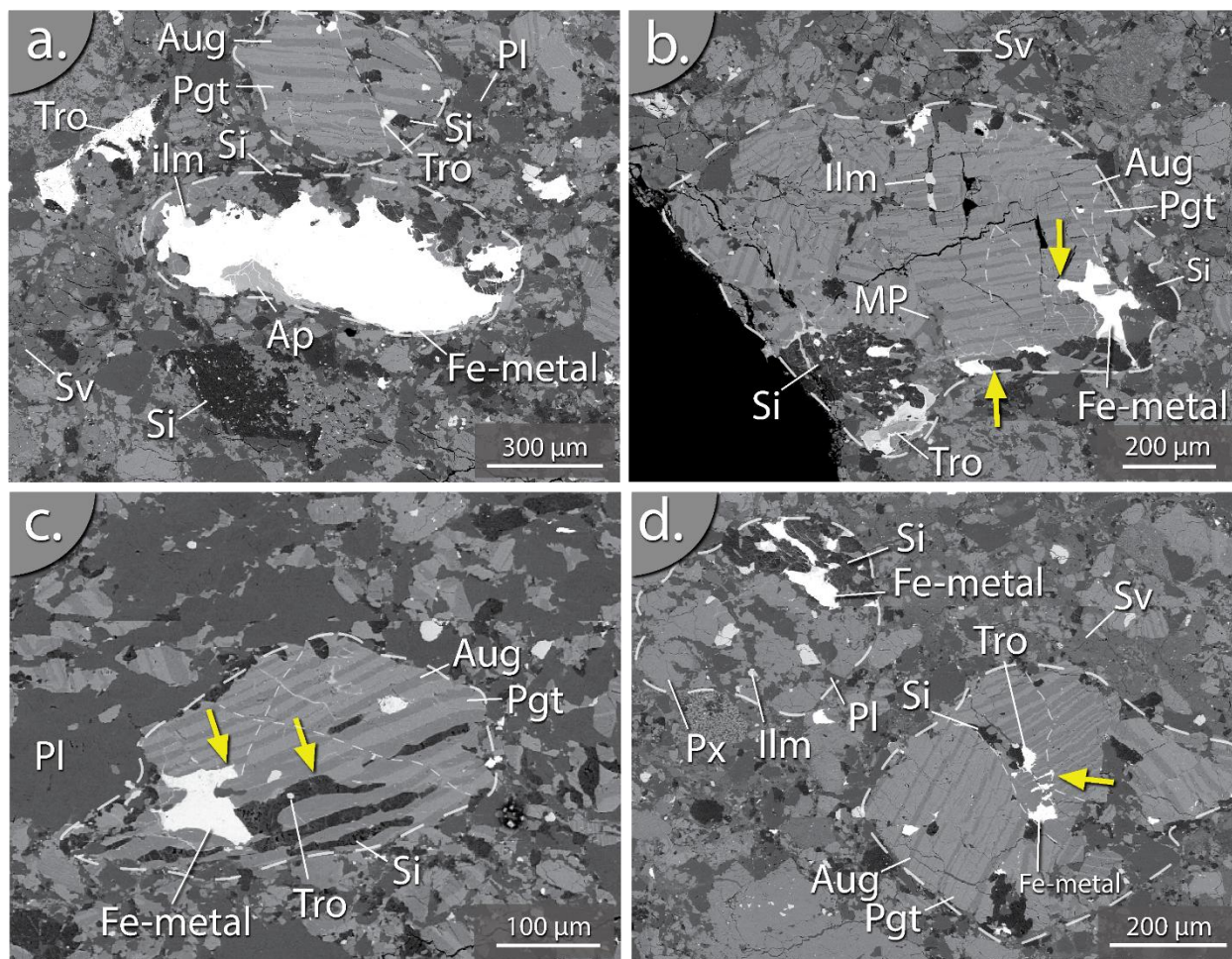


## 117 4. METALLIC IRON IN ERRACHIDIA 002 AND NWA 11911

### 118 4.1. ERRACHIDIA 002

119 Fe-metal in Errachidia 002 is solely present in pyroxene found in L2 (Fig. 7). EPMA data  
120 shows that the iron metal consists of very low Ni content (mostly below the detection limit of  
121 0.04 wt%), and up to 0.05 wt% Co (Ni/Co = 0.8; Table 2). The metallic iron in the clast in Figure  
122 7a is 800  $\mu\text{m}$  in length, and contains apatite (with CaO, P<sub>2</sub>O<sub>5</sub>, FeO, F, and Cl contents of 54 wt%,  
123 40 wt%, 2 wt%, 3.6 wt%, and 0.05 wt%, respectively), and silica grains up to 10  $\mu\text{m}$  in size (see  
124 close-up images in Fig. S1). The Ca, Si, and S elemental maps of this clast (Fig. 8a) show the  
125 following: (1) augite (En<sub>28</sub>Fs<sub>30</sub>Wo<sub>42</sub>) becomes abundant in the vicinity of the metal, whereas  
126 pigeonite becomes either rare or absent; (2) there is a high abundance of silica associated with  
127 the metal. This is not observed in the clasts where metal is not detected (Fig. 2e), and; (3) troilite  
128 is nearly absent in the proximity of the clast and the metal.

129



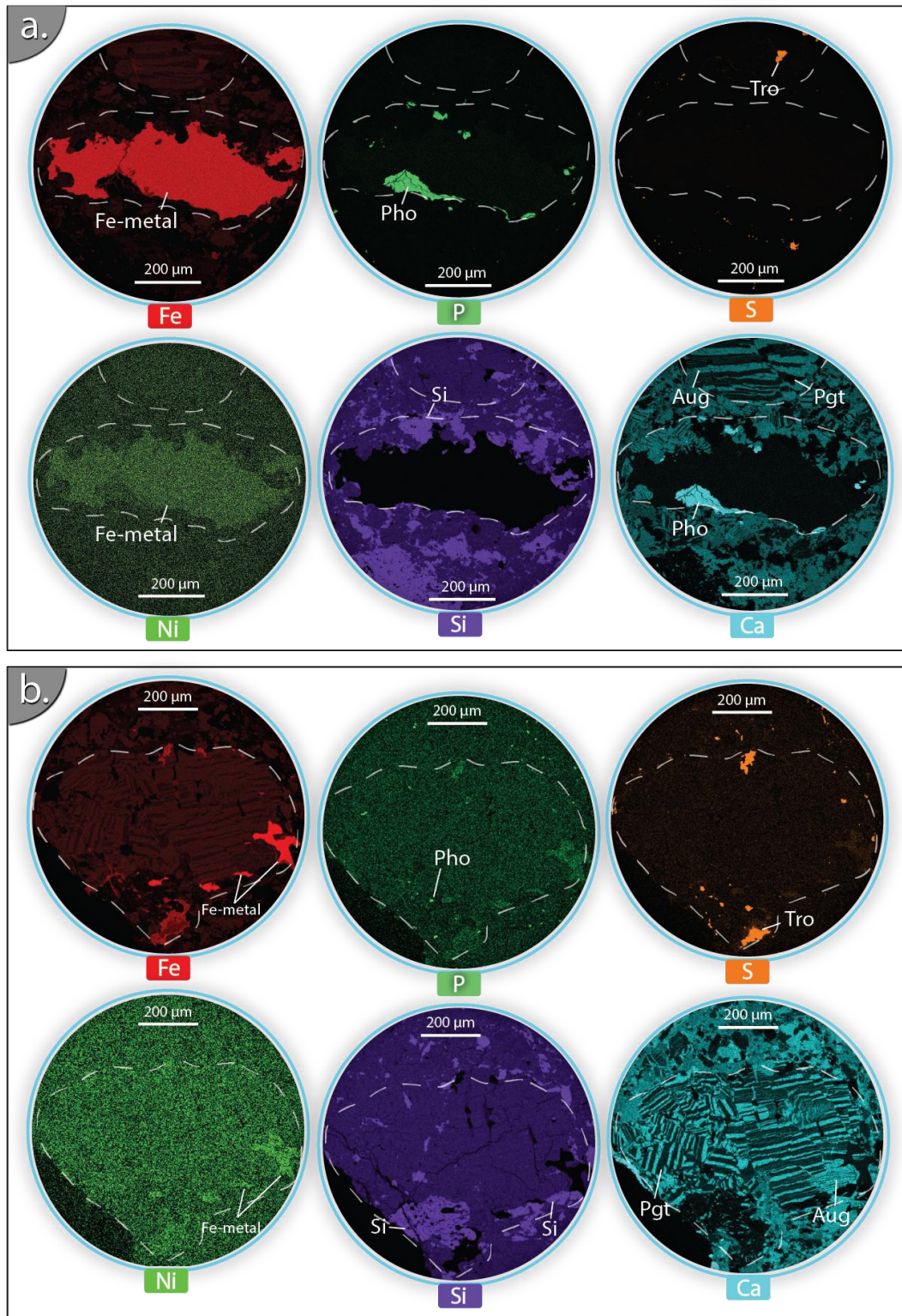
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131 **Fig. 7.** Metallic iron in Errachidia 002. (a) Fe-metal in a pyroxene associated with silica. (b, c, d) Fe-metal  
 132 in clasts composed mainly of equilibrated pyroxene with pigeonite host containing frequently bended or  
 133 faulted exsolution lamellae of augite (faulting surfaces are marked with dashed lines). Associated mineral  
 134 phases with Fe-metal are silica and minor troilite. Note the presence of Fe-metal and silica in a  
 135 compositionally different clast (with minor to no exsolution lamellae of augite; see Fig. S1e in the  
 136 supplementary material) in the upper left area in (d). X-ray elemental maps of the clast in (a) and (b)  
 137 are given in Fig. 8. The yellow arrows show the protrusion of Fe-metal and silica in pigeonite, between augite  
 138 exsolution lamellae. Pgt = pigeonite; Aug = augite; Pl = plagioclase; Si = silica; Ap = apatite; Ilm =  
 139 ilmenite; Tro = troilite; Sv = shock vein; MP = melt pocket.

140 Compositionally similar iron metals were also identified in other pyroxene fragments in L2  
 141 (Fig. 7b, c, and d). The pyroxene fragment shown in Fig. 7b is equilibrated, and contains faulted  
 142 and displaced exsolution lamellae of augite ranging from 3 to 14 μm in thickness (see Ca  
 143 elemental maps in Fig. 8b). Silica is either associated with iron metal, or with troilite (Fe, Si and  
 144 S elemental maps in Fig. 8b). In a similar way as in the clast in Fig. 7a, augite lamellae become  
 145 abnormally thicker (up to 50 μm thick), and less spaced in vicinity of the metal (see Ca map in  
 146 Fig. 8b, and the close-up BSE image in Fig. S1d). Another fragment of pyroxene consisting of

147 host pigeonite, displaced augite lamellae, porous silica, iron metal and troilite is shown in Fig.  
148 [7c](#). The porous silica replaces the host pigeonite, following the direction of the augite lamellae.  
149 Iron metal up to 80  $\mu\text{m}$  in length often protrudes the host pigeonite following the same direction.  
150 Troilite is found either in host pigeonite, or as 5- $\mu\text{m}$ -sized euhedral inclusions in silica. We also  
151 identified comparable features in the pyroxene fragments shown in [Fig. 7d](#), [Fig. S1e](#) and [Fig.](#)  
152 [S1f](#).





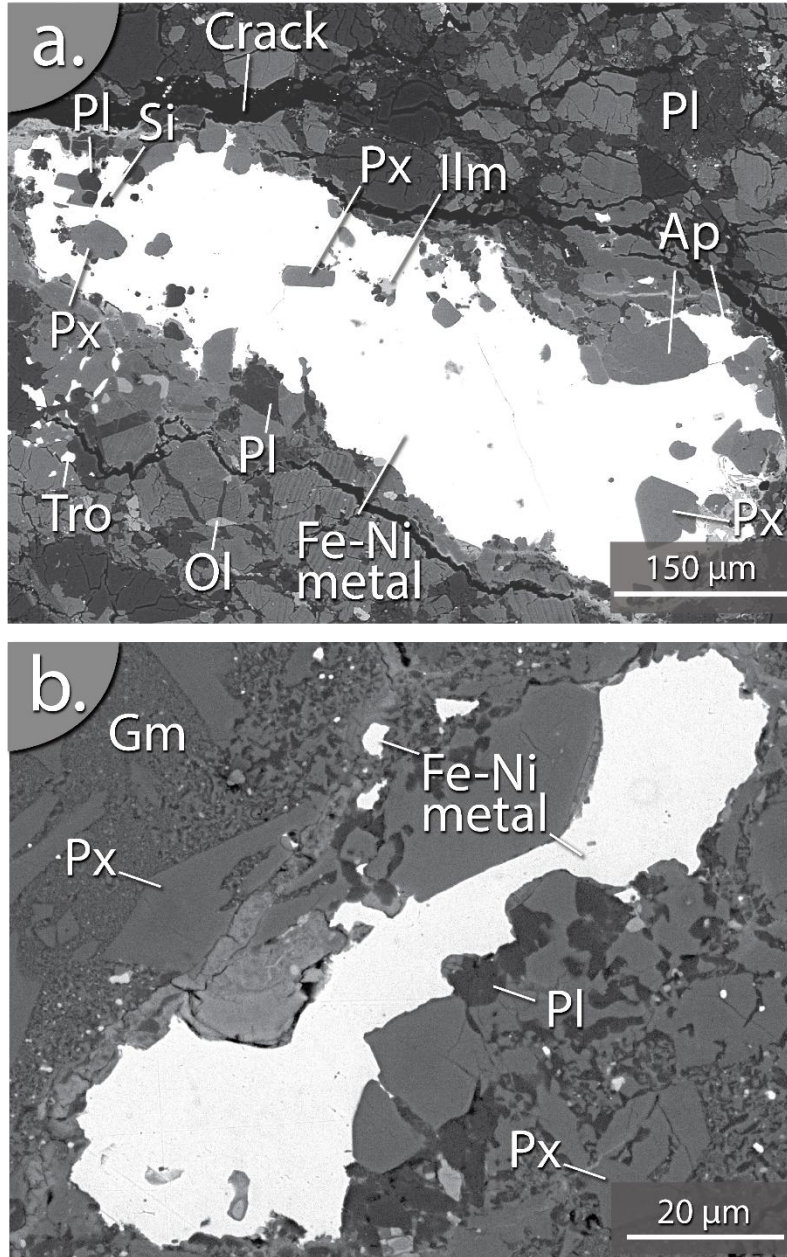
153

154 **Fig. 8.** X-ray elemental maps (Fe, Ni, P, Si, S, and Ca) of Fe-metal in Errachidia 002. The upper maps (a)  
 155 show the elemental distribution in the clast shown in Fig. 7a. The lower maps (b) show the elemental  
 156 distribution in the clast shown in Fig. 7b. Pgt = pigeonite; Aug = augite; Si = silica; Pho = phosphate; Tro  
 157 = troilite.



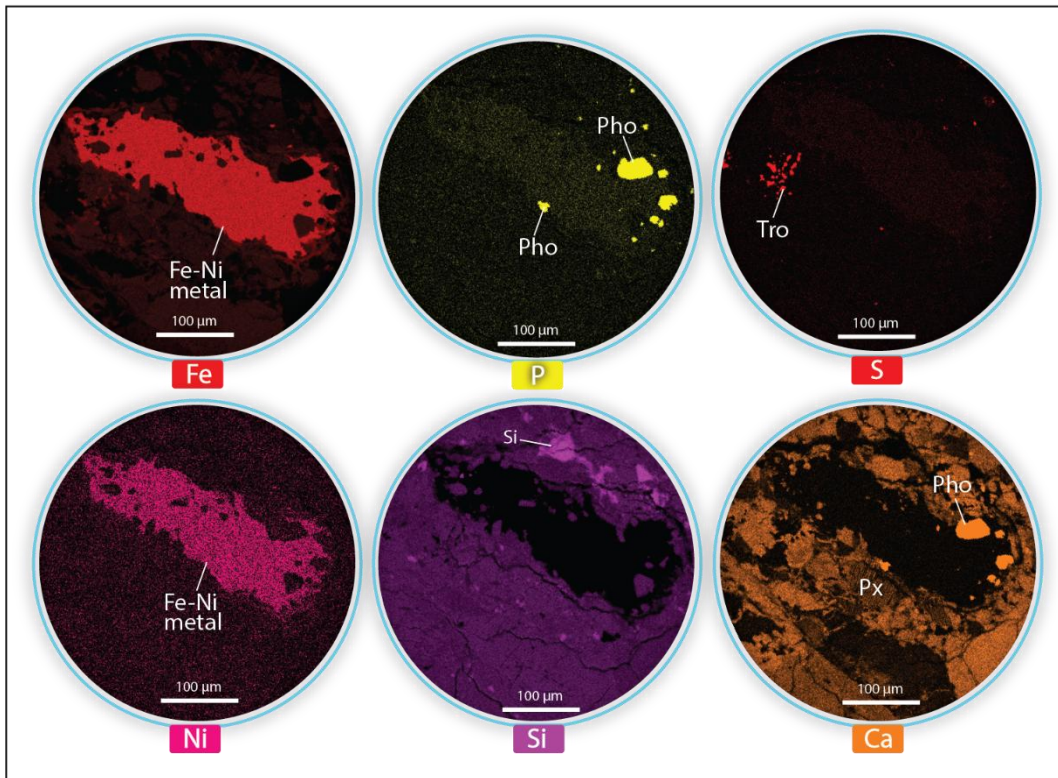
158 **4.2. NWA 11911**

159 Fe-Ni metal in NWA 11911 is found enclosed in the matrix, or in the impact melt clast (Figs.  
160 4, 9, and 10; Fig. S2), and has an average composition of 97.5 wt% Fe, 2.8 wt% Ni, and 0.6 wt%  
161 Co (n = 5; Ni/Co = 4.2; Table 2). The metal grain (~360×100 μm) in Fig. 9a contains fragments  
162 of pyroxene (~25 μm in size), plagioclase, silica, apatite, and ilmenite (see X-ray elemental maps  
163 in Fig. 10, and close-up BSE images in Fig. S2a). The composition of low-Ca pyroxene enclosed  
164 in metal is  $\text{En}_{38}\text{Fs}_{60}\text{Wo}_2$  in average (n = 4; Fe/Mn = 34), which is comparable to the composition  
165 of abutting pyroxene in the matrix ( $\text{En}_{38}\text{Fs}_{59}\text{Wo}_3$ ; n = 4; Fe/Mn = 33.6). Plagioclase has a  
166 composition ranging from  $\text{An}_{73}$  to  $\text{An}_{90}$  in metal, and from  $\text{An}_{78}$  to  $\text{An}_{91}$  in the matrix near the  
167 metal grain. FeO and  $\text{TiO}_2$  contents of ilmenite within the metal are typical of eucrite ilmenite,  
168 and are 46 wt% and 50 wt%, respectively. The apatite grains in the metal contain 55 wt% CaO,  
169 41 wt%  $\text{P}_2\text{O}_5$ , and ~3 wt% FeO (see also the P elemental map in Fig. 10). Fig. 9b shows a  
170 metallic iron grain enclosed in the impact melt clast, displaying the same composition as the  
171 metal in Fig. 9a (see also Fig. S2b). Skeletal pyroxene (20 μm) in vicinity of the metal has a  
172 range of compositions of  $\text{En}_{38-40}\text{Fs}_{55-58}\text{Wo}_2$ , and an average Fe/Mn ratio of 33. Tiny inclusions of  
173 metal ( $\leq 5$  μm across) are also detected in the devitrified aphanitic matrix, or within skeletal  
174 pyroxene.



175

176 **Fig. 9.** Backscattered electron images of Fe-Ni metals found in NWA 11911. (a) Fe-Ni metal found in the  
 177 matrix of NWA 11911. (b) Fe-Ni metal enclosed in the impact melt clast. Close-up images of these grains  
 178 are presented in Fig. S2 in the supplementary material. Px = pyroxene; Pl = plagioclase; Si = silica; Ol =  
 179 olivine; Ap = apatite; Ilm = ilmenite; Tro = troilite; Gm = glassy and devitrified groundmass.



180

181 **Fig. 10.** X-ray elemental maps (Fe, Ni, P, Si, S, and Ca) of the Fe-Ni metal found in the matrix of NWA  
 182 11911, and shown in the BSE image in Fig. 9a. Px = pyroxene; Si = silica; Pho = phosphate; Tro =  
 183 troilite.

## 184 5. DISCUSSION

### 185 5.1. EVIDENCE OF LITHOLOGIC MIXING BY IMPACTS IN ERRACHIDIA 002 AND NWA 11911

186 Unbrecciated eucrites are considered pristine (with no lithologic mixing), and are the best tool  
 187 for modeling the formation and the magmatic evolution of the HED parent body (Mayne et al.,  
 188 2009). On the other hand, eucrites that are brecciated, and especially those polymict (composed  
 189 of two or more lithologies, with <10% diagenetic material; Delaney et al., 1983), offer a window  
 190 into the collisional environment and the post-magmatic processes that controlled their parent  
 191 body surface features. In this study, we examined the mineralogy and the petrology of Errachidia  
 192 002 and NWA 11911, which are two brecciated eucrites found in Morocco, in order to constrain  
 193 their formation mechanisms. These rocks share a common origin as evidenced by their pyroxene  
 194 Fe/Mn ratio of 31-33, which is in the range of values found in eucrites (Papike et al., 2003). This  
 195 genetic link is also supported by the compositions of plagioclase found in both meteorites (An<sub>72-95</sub>),  
 196 which fall within the compositional range of eucritic plagioclase (Mittlefehldt, 2015).

197 **5.1.1. Errachidia 002**

198 Our results show that the formation of Errachidia 002 involves multiple impact events,  
199 resulting in the excavation and the mixing of various eucritic and diogenitic lithologies. This  
200 meteorite is composed of two portions (L1 and L2; Fig. 1), each with its distinct formation  
201 history.

202 **5.1.1.1. Lithology 1 (L1)**

203 L1 consists of a mixture of upper crust basaltic lithologies, as well as at least one lower crust  
204 gabbroic lithology. This is supported by the textures and the major mineral compositions of the  
205 clasts investigated. The clasts in Fig. 2a and Fig. 2b are fine-grained and exhibit subophitic  
206 textures, which is consistent with the grain sizes and the textures of basaltic eucrites  
207 (Mittlefehldt, 2015). This is supported by the compositions of their pyroxene ( $\text{En}_{32-35}$ ), which are  
208 in the range of values measured in basaltic eucrites ( $\text{En}_{45-33}$ ; Fig. 3a; Mittlefehldt et al., 1998;  
209 Mayne et al., 2009). Pyroxene in these clasts contains exsolution lamellae of augite, implying a  
210 metamorphic event (i.e., global crustal metamorphism; Yamaguchi et al., 1996), that erased the  
211 initial igneous zoning. The effect of this event is also observed in plagioclase, which contains  
212 micron-sized exsolved inclusions that follow crystallographic directions (i.e., clouding of  
213 plagioclase; Harlow and Klimentidis, 1980). The clast shown in Fig. 2c represents a cumulate  
214 eucrite lithology, as it exhibits a coarse-grained, equigranular texture, and it is devoid of late-  
215 stage mesostasis. This is also supported by its pyroxene Mg-rich composition ( $\text{Mg}\# = 43$ ), which  
216 plots near the pyroxene compositional field of cumulate eucrites (Fig. 3a). The fine-grained  
217 clasts have an impact-related origin (Fig. 2d); this is evidenced by the presence of rounded  
218 eucritic fragments along with skeletal pyroxene, in the fine-grained matrix composed of  
219 plagioclase and pyroxene. Similar clasts have been identified in the Allan Hills 76005 pairing  
220 group, which formed during a process of heating and melting followed by rapid cooling of target  
221 eucritic material (Righter and Holmwood, 2020).

222 **5.1.1.2. Lithology 2 (L2)**

223 L2 is as well a mixture of various lithologies. The compositions of host pigeonite ( $\text{En}_{35}\text{Fs}_{60}$ )  
224 in the equilibrated pyroxene fragments in Fig. 2e is in the range of basaltic eucrite compositions  
225 (Mayne et al., 2009). The degree of equilibration of these pyroxene fragments are consistent with  
226 type 6 eucrites, which are characterized by a good separation between low- and high-Ca



227 pyroxene (Takeda and Graham, 1991). The compositions of these two phases (host pigeonite and  
228 exsolution lamellae of augite) allow the estimation of the equilibration temperature using the  
229 QUILF (quartz-ulvospinel-ilmenite-fayalite) program (Andersen et al., 1993). The equilibration  
230 temperature obtained is  $732 \pm 40$  °C, which is in the range of the temperatures (650-1100 °C)  
231 calculated in basaltic eucrites affected by widespread crustal metamorphism (Yamaguchi et al.,  
232 1996; Mayne et al., 2009). Evidence of impact shock and melting are present in the glassy clast  
233 in Fig. 2f; its formation is the result of superheating, followed by rapid cooling of eucritic  
234 material, as indicated by the presence of relict eucritic fragments enclosed in the glassy  
235 groundmass.

236 The texture, the mineralogy, and the compositions of the olivine-bearing clasts (Fig. 2g, h)  
237 suggest that they represent a ferroan noritic diogenite lithology; a transitional lithology to  
238 cumulate eucrites (Mittlefehldt, 2015) that likely formed in plutons intruding the basaltic crust.  
239 This is indicated by the following lines of evidence. (1) the presence of orthopyroxene as the  
240 dominant phase, with compositions (En<sub>59-61</sub>) plotting in the field of cumulate eucrites (En<sub>65-46</sub>)  
241 and slightly ferroan than pyroxene compositions in the Yamato type B noritic diogenites (En<sub>64</sub>;  
242 Mittlefehldt, 2015) and NWA 8744 (En<sub>58</sub>; Irving et al., 2016). (2) The presence of > 10 vol% of  
243 calcic plagioclase with an endmember composition of ~An<sub>95</sub>, which is in the range of plagioclase  
244 compositions in cumulate eucrites, and diogenites as well (An<sub>82-95.7</sub>; Beck and McSween, 2010).  
245 (3) the occurrence of various proportions of moderately magnesian olivine with a composition of  
246 Fo<sub>51-52</sub>, which is comparable to the composition of olivine in the noritic diogenite NWA 8744  
247 (Fo<sub>51</sub>; Irving et al., 2016), but more ferroan than olivine in the noritic diogenite NWA 8321 (Fo<sub>75</sub>;  
248 Zhang et al., 2020). In summary, Errachidia 002 bears evidence of a complex succession of post-  
249 crystallization events such as thermal metamorphism and impacts events. The latter caused  
250 mixing of upper (basaltic) and lower (noritic diogenite) lithologies, and also enabled the  
251 formation of impact-generated features such as shock veins, as well as glassy and fine-grained  
252 clasts.

### 253 **5.1.2. NWA 11911**

254 The formation history of NWA 11911 is as complex as that of Errachidia 002. This rock is  
255 composed of equilibrated and unequilibrated, monomineralic and polymineralic fragments with  
256 mineral compositions in the range of basaltic lithologies. This indicates mixing of upper crust

257 rocks originated from various depths given the fact that, during rapid lava eruptions on the  
258 surface of (4) Vesta, basalts that erupted first were buried and therefore metamorphosed, whereas  
259 those that erupted later were less affected by thermal metamorphism and preserved their initial  
260 igneous textures and compositions (Yamaguchi et al., 1996; Yamaguchi et al. 1997).

261 After and perhaps during these magmatic and metamorphic events, impact processes caused  
262 the formation of impact-engendered features such as shock veins and impact melt clasts (Fig. 5a,  
263 5b). According to Stöffler et al. (2018), the formation of shock veins is the result of shock wave  
264 propagation during an impact event. Their presence in mafic rocks such as eucrites indicates a  
265 shock stage S4 or S5, with equilibration shock pressures up to 28 GPa or more and post-shock  
266 temperatures ranging from 200 to up to 900 °C. The texture displayed by the dark, glassy clast  
267 embedded in the fragmental matrix of NWA 11911, and shown in Fig. 5b, could be best  
268 explained by impact melting of target eucritic rocks. Comparable dark clasts have been described  
269 in some Allan Hills 76005 paired group of eucrites by Righter and Holmwood (2020). In their  
270 work, they suggested that these clasts formed as a result of superheating and rapid cooling of  
271 surface material. This is consistent with the features observed in the impact melt clast of NWA  
272 1191. The presence of zoned pyroxene microlites and the glassy matrix implies heating and  
273 melting of the target eucritic rocks, followed by rapid cooling (Fig. 5b). The occurrence of  
274 trapped mineral fragments with partially melted margins indicates their incorporation and  
275 reaction with the melted material prior to its cooling. These features are indicators of a shock  
276 pressure of > 55 GPa with a post-shock temperature of > 1100 °C (see the shock metamorphism  
277 classification scheme of mafic rocks by Stöffler et al. 2018). The Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, CaO, and Na<sub>2</sub>O  
278 contents of the glass in the shock vein and the impact melt clast are significantly similar, and  
279 confirm that the target rocks were mainly basaltic eucrite lithologies (Barrat et al., 2009).

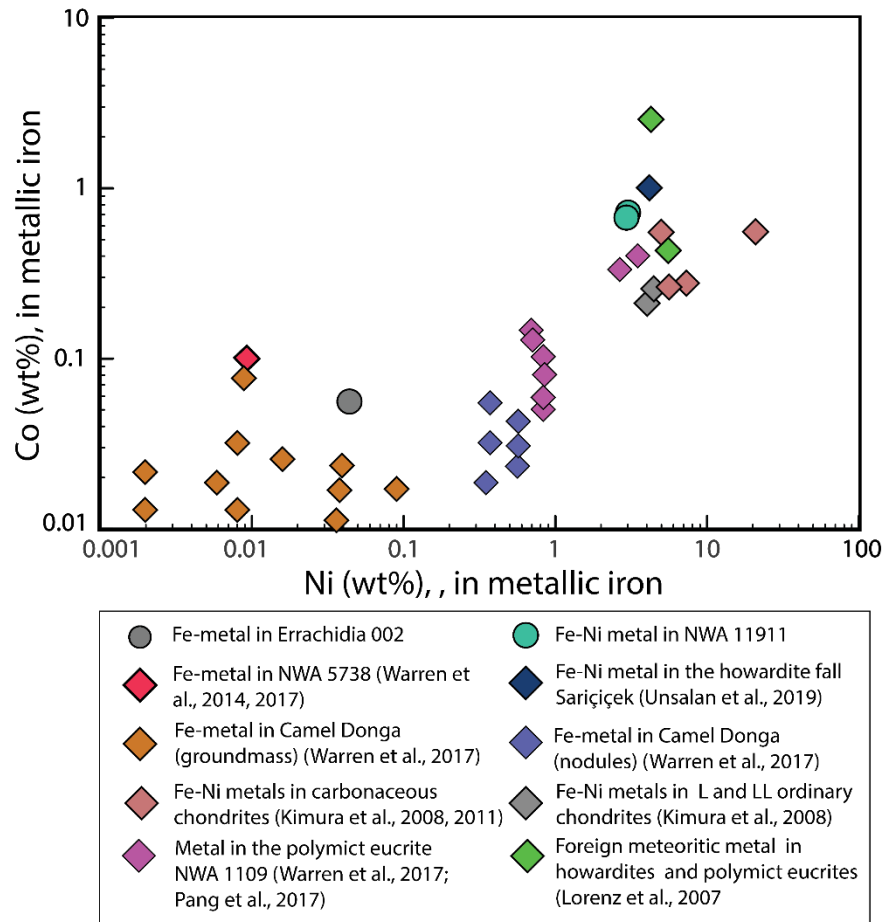
280 Impact processes also played a major role in the formation of secondary alteration features in  
281 NWA 11911 as previously demonstrated by Shisseh et al. (2023). The formation of fractures  
282 allowed the circulation of aqueous fluids causing Fe-enrichment in pyroxene, as well as the  
283 deposition of fayalitic olivine associated with Ca-rich plagioclase, Cr-spinel, apatite, and troilite.  
284 In brief, NWA 11911 is a polymict eucrite that records multiple post-magmatic processes such as  
285 crustal thermal metamorphism, impact shock and melting, as well as fluid-assisted metasomatic  
286 reactions.

## 287 **5.2. ORIGIN AND IMPLICATION OF METTALIC IRON IN POLYMICT EUCRITE BRECCIAS**

288 The occurrence of Fe-metal in eucrites has been attributed to reducing magmatic conditions,  
289 post-crystallization processes engendered by thermal metamorphism, impact shock, or  
290 metasomatism (Duke, 1965; Guo et al., 2021; Lorenz et al., 2007; Palme et al., 1988; Warren et  
291 al., 2014; Shisseh et al. 2022). Based on textural and mineralogical observations, as well as the  
292 compositional data, we infer that the iron metals in the polymict eucrites Errachidia 002 and  
293 NWA 11911 have distinctly different origins.

#### 294 **5.4.1. Errachidia 002**

295 Fe-metals in Errachidia 002 are nearly pure and contain very low Ni abundances, which rules  
296 out their origin from an exogenous impactor (see discussion below regarding Fe-Ni metal found  
297 in NWA 11911). In the plot of Ni versus Co (wt%) shown in [Fig. 11](#), the metallic iron  
298 composition plots near the Ni-Co compositional range of pure Fe-metals found in NWA 5738,  
299 which are suggested to have formed by complex secondary alteration processes involving  
300 aqueous fluids (Warren et al., 2014). It also plots near the Ni-Co values measured in Fe-metals  
301 found in Camel Donga groundmass that are believed to be products of troilite alteration by H<sub>2</sub>O-  
302 rich fluids (Warren et al., 2017).



303

304 **Fig. 11.** Ni (wt%) versus Co (wt%) of iron metal in Errachidia 002 and in NWA 11911. Values measured  
 305 in iron metal in chondrites, polymict eucrites, and howardites are also plotted for comparison.

306 Although these secondary, nearly pure Fe-metals are compositionally quite similar to  
 307 metallic iron in Errachidia 002, we doubt that their formation scenarios are identical for the  
 308 following reasons: (1) Fe-metals in NWA 5738 are large (up to 3.4 mm long in some cases) and  
 309 are shaped like veins that cut both pyroxene and plagioclase (Warren et al., 2014). This is not  
 310 observed in Errachidia 002 considering that Fe-metals are not vein-shaped, they mostly occur in  
 311 individual pyroxene grains, and they do not extend to adjacent matrix or cut through any other  
 312 mineral phases. Also, we did not detect any other type of secondary alteration features (fayalitic  
 313 or Ca-rich plagioclase veinlets) identified by Warren et al. (2014) in NWA 5738, which  
 314 constitutes further evidence that the scenario that formed the latter meteorite's Fe-metals is  
 315 unlikely to explain the formation of metallic iron in Errachidia 002. (2) The formation of Fe-  
 316 metals in Camel Donga groundmass likely involved the alteration of troilite by H<sub>2</sub>O fluids  
 317 released by impact heating of CM-like material (Warren et al., 2017), following the reaction:



318  $3\text{FeS} + 2\text{H}_2\text{O} = 3\text{Fe} + 2\text{H}_2\text{S} + \text{SO}_2$  (Frost, 1985). This reaction is unlikely given that troilite is  
319 present in some cases near Fe-metal (Fig. 7). In addition, since silica is not a by-product of this  
320 reaction, it fails to explain the widespread occurrence of silica in association with Fe-metal in all  
321 pyroxene grains enclosing it (Fig. 7; Fig. 8), as well as the marked replacement of FeO-rich  
322 pigeonite by Fe-metal (Fig. 7).

323 To explain the formation of pure metallic iron in Errachidia 002, we suggest a mechanism  
324 similar to that previously proposed by Palme et al. (1988). These authors demonstrated that an  
325 increase of temperature (up to  $\sim 1000$  °C) during an impact event can cause troilite decomposition  
326 and generate  $\text{S}_2$  and  $\text{SO}_2$  vapors. These gases will subsequently react with FeO in pyroxene to  
327 produce metal and silica. In more detail, at first, heating will trigger the decomposition of troilite  
328 following this reaction:  $2\text{FeS} = 2\text{Fe} + \text{S}_2$  (g). Then,  $\text{S}_2$  vapor will reduce more troilite and FeO in  
329 pyroxene producing pure Fe-metal and silica by the reaction:  $2\text{FeSiO}_3 + \frac{1}{2}\text{S}_2 = 2\text{Fe} + 2\text{SiO}_2 +$   
330  $\text{SO}_2$  (g). The production of  $\text{S}_2$  and  $\text{SO}_2$  in both reactions will further reduce pyroxene to metal  
331 and silica. This successfully explains the following: (1) The presence of Fe-metals solely in  
332 pyroxene, and more precisely in host FeO-rich pigeonite in equilibrated pyroxene grains (Fig. 7).  
333 This indicates that S-vapors reacted with FeO in pyroxene to produce metal, leaving high-Ca  
334 pyroxene (augite) in their vicinity. The protrusion of Fe-metal in host pigeonite (Fig. 7b, c, d;  
335 Fig. S1d), but not in exsolved augite lamellae, is additional compelling evidence for this  
336 selective reaction. This also implies that this process occurred after the thermal metamorphic  
337 event that caused the equilibration of pyroxene, and also prior to the assembly of the breccia,  
338 since iron metal is confined to clasts and is not found in the abutting matrix. (2) The reduction of  
339 FeO in pyroxene would produce a great amount of silica. This is consistent with the occurrence  
340 of an unusually high amount of silica in association with Fe-metal in all examined metal-bearing  
341 clasts (Fig. 1; Fig. 7; Fig. 8). This process is well exemplified in Fig. 7c (see yellow arrows),  
342 given that silica is replacing host pigeonite, between the exsolution lamellae of augite. (3)  
343 Troilite is depleted in Fe-metal-bearing pyroxene clasts (see the S map of the large pyroxene  
344 grain in the center of Fig. 8a). Yet, we detected troilite in the pyroxene clast shown in Fig. 7b  
345 (see also S maps in Fig. 8b), as well as in silica and pyroxene in the form of inclusions as  
346 exemplified in Fig. 7c, which indicates an incomplete decomposition reaction implying that the  
347 heating event was of short duration. This was also noted by Palme et al. (1988), as they found  
348 sulphide droplets in close proximity of Fe-metals in the eucrite Camel Donga.

349 Unlike the clasts shown in Fig. 7b, 7c, and 7d, we noted the occurrence of a large apatite  
350 grain in the Fe-metal shown in Fig. 7a. Warren et al. (2014) reported apatite in the vicinity of Fe-  
351 metal veins in NWA 5738, and suggested that this mineral phase is likely a secondary alteration  
352 product. Camel Donga's groundmass metal is also associated with apatite that occurs as clusters  
353 of 100- $\mu\text{m}$ -sized grains; Warren et al. (2017) attempted to explain its formation by a process  
354 similar to that responsible of the formation of phosphates (merrillite) in mesosiderites, but  
355 eventually ruled out this scenario. Association of silica and merrillite with metal is extensively  
356 documented in mesosiderites (Harlow et al., 1982; Iannini et al., 2022; Mayne et al., 2023). The  
357 presence of these phases is well explained by a process of reduction of silicates and oxidation of  
358 P dissolved in metal (Harlow et al., 1982; Warren et al., 2017). In our case, the Fe-metal is  
359 associated with a phosphate phase as well as silica (Fig. 7a; P and Si X-ray maps in Fig. 8a),  
360 which could suggest that they formed by a similar process as that in mesosiderites. Nevertheless,  
361 there are several lines of evidence that argue against this scenario. First, Fe-metals in  
362 mesosiderites contain a significant abundance of Ni (up to ~6 wt% Ni in most cases; Wasson et  
363 al., 1974; Warren et al., 2017; Caves, 2019; Mayne et al., 2023). This is not the case in all Fe-  
364 metals found in Errachidia 002, as their Ni content is below our Ni EPMA detection limit of 0.04  
365 wt%. Second, our EPMA analysis results from Fe-metals that do not contain a phosphate phase  
366 such as the one identified in the large metallic iron in Fig. 7a indicate that their P content is  
367 below the detection limit ( $<0.02$  wt%), ruling out that the P that formed apatite in the large  
368 apatite-bearing Fe-metal was dissolved in it. In addition, we did not detect schreibersite, which  
369 forms in mesosiderites by exsolution of P dissolved in metal as the temperature slowly drops  
370 (Harlow et al., 1982). Finally, the oxidation product of P dissolved in mesosiderites is merrillite  
371 and not apatite. The phosphate phase found in association with the Fe-metal in Fig. 7a is apatite,  
372 and not merrillite. Nevertheless, it is important to mention that various authors (Douce et al.,  
373 2011; Sarafian et al., 2013; Warren et al., 2017) demonstrated that it is possible to form apatite  
374 from merrillite by addition of halogens.

375 Another mechanism that can account for the formation of apatite in Errachidia 002's pure Fe-  
376 metal is the interaction of P-vapors with Ca released from Fe-rich pigeonite during its  
377 decomposition to Fe-metal and silica. P-vapors were likely present on the surface of (4) Vesta,  
378 and their formation mechanism involved volatilization of P-bearing material as reported by  
379 Zhang et al. (2013) in the brecciated eucrite NWA 2339. According to these authors, P-vapors

380 reacted with Ca released from plagioclase and pyroxene after their sulfurization and  
381 subsequently formed merrillite. The apatite-metal-bearing pyroxene clast in Errachidia 002 (Fig.  
382 7a) is basaltic in composition, and late-stage mesostasis in eucritic basalts consists mostly of  
383 late-stage phases such as phosphates (mainly apatite) and troilite (Patzer and McSween, 2012),  
384 which could be a great source of P- and S-vapors when heated during a high energetic impact.  
385 The distribution of mesostasis in eucrites is also heterogenous. This could explain why there is a  
386 substantial amount of Fe-metal, silica, and apatite in that particular grain (Fig. 7a) and not in the  
387 others (Fig. 7b, c, d; Fig. S1e, f), as nearby mesostasis-rich areas were heated to produce  
388 abundant S-vapors that reacted with FeO in pyroxene to form pure Fe-metal and silica, as well as  
389 P-bearing vapors that combined with Ca released from pyroxene to form apatite. Note that an  
390 origin of these vapors from the impactor itself cannot be ruled out entirely.

#### 391 **5.4.2. NWA 11911**

392 Eucrites contain usually metal with low Ni content (<0.01-0.1 wt% Ni; Yamaguchi et al.,  
393 2006), as the majority of nickel has segregated into the metallic core of their parent body. The  
394 metal in NWA 11911 has 2.8 wt% Ni, and plots in the Ni-Co field of metals found in chondrites,  
395 as well as foreign metals in polymict eucrites and howardites (Fig. 11). This provides a strong  
396 indication of contamination by projectiles, most likely derived from a nearby impact event  
397 involving a metal-bearing impactor. This collision caused fragmentation and melting of eucritic  
398 rocks, followed by their mixing with exogenous metal projectiles, as indicated by the presence of  
399 minerals with compositions in the range of eucrite mineral phases incorporated in the Fe-Ni  
400 metal (Fig. 9a), and the presence of metal in the impact melt clast with a glassy matrix displaying  
401 compositions consistent with basaltic eucrite target rocks (Fig. 9b).

#### 402 **5.5. FORMATION OF FINE-GRAINED ASSEMBLAGES IN NWA 11911**

403 A few clasts in NWA 11911 exhibit distinct textures and mineralogies compared to the  
404 monomineralic and polymineralic basaltic clasts found in the matrix. The clast shown in Fig. 5c  
405 displays a sulfide-rich fine-grained texture, marked by the presence of an assemblage of Fe-rich  
406 pigeonite, Mg-rich augite, silica, troilite, and ilmenite. Note that these assemblages are only  
407 found in pyroxene, and do not occur in plagioclase. Typically, one would think that these are  
408 mesostasis areas given that some of these phases (mainly silica, troilite, and ilmenite) are among

409 the latest mineral phases to crystallize in a eucritic magma (Yamaguchi et al., 2009). This  
410 interpretation is unlikely considering that mesostasis areas in eucrites are usually dominated by  
411 silica, and their shape is controlled by the surrounding early-formed mineral phases (Mayne et  
412 al., 2009; Shisseh et al., 2022). The presence of subequal amount of troilite and silica, as well as  
413 the presence of two fine-grained pyroxene phases with differently distinct compositions ( $\text{En}_{26-}$   
414  $_{28}\text{Wo}_{43-43.5}$  and  $\text{En}_{23.8-26.6}\text{Wo}_{28.2-29.8}$ ) than Fe-rich host pyroxene ( $\text{En}_{33}\text{Wo}_9$ ) implies a mechanism  
415 of pyroxene sulfurization by S-vapors. Similar process was described by Zhang et al. 2013 in  
416 NWA 2339. According to these authors, dry S-vapors formed by volatilization of S-bearing  
417 material on the surface (4) Vesta are responsible for the formation of secondary minerals that  
418 replace primary Fe-rich pyroxene, such as Mg-rich augite, Mg-rich ferrosilite, silica, troilite and  
419 ilmenite. Another plausible effect of sulfurization includes the occurrence of vesicles and  
420 inclusions of troilite in silica (see lower left corner in Fig. 5c). Sulfurization of eucritic silica was  
421 described in the monomict basaltic eucrite NWA 11591, resulting in SRTs (sulfide-rich  
422 replacement textures) with porous regions composed of quartz and troilite along the fractures and  
423 rims (Huang et al., 2020). These authors explained the formation of troilite by a reaction of S-  
424 vapors with FeO transported by S-vapors from pyroxene or Fe-rich mesostasis, or with metallic  
425 Fe.

426 The texture and mineral assemblage (two pyroxene phases, silica, and troilite) observed in  
427 the lithic clast shown in Fig. 5d is considerably similar to what we described above. However,  
428 some differences arise such as the presence of Fe-rich olivine ( $\text{Fa}_{81}$ ) associated with silica in the  
429 form of lamellae and vermicules, as well as the fact that they display a sharp boundary with host  
430 pyroxene. This suggests that this clast is a symplectite formed by cooling of melts (Rasmussen et  
431 al., 2008), or reheating by magmatic intrusions or during impact events (Barrat et al. 2012).  
432 Symplectites showing similar textures and mineralogies have been previously described in  
433 terrestrial rocks, HED meteorites, lunar meteorites, and Martian meteorites (Aramovich et al.,  
434 2002; Liu et al., 2009; Patzer and McSween, 2012). To explain their formation, Rost et al. (2009)  
435 invoked a mechanism involving the breakdown of pyroxferroite, which occurred under rapid  
436 cooling and at low pressures. The presence of this symplectitic clast in NWA 11911 provides  
437 evidence that Fe-rich evolved eucritic lithologies exist on (4) Vesta, in a similar way as other  
438 planetary objects such as Earth, the Moon, and Mars.



439 **CONCLUSION**

440 Errachidia 002 and NWA 11911 are eucrite finds recovered in Morocco. Both rocks are  
441 polymict as they consist of fragments originated from various upper and lower crust lithologies.  
442 Errachidia 002 is characterized by the presence of two lithologies consisting of basaltic,  
443 cumulate, and noritic diogenite debris. NWA 11911 is composed mainly of unequilibrated and  
444 equilibrated basaltic fragments, as well as some impact-generated features like shock veins and  
445 impact melts. Both rocks consist of a fragmental matrix with fine-grained fragments of typical  
446 eucrite minerals.

447 We investigated metallic irons found in Errachidia 002 and NWA 11911 to determine their  
448 origin and their implication for the collisional history of the eucrite parent body. Our results  
449 show that Fe-metals in Errachidia 002 solely occur in pyroxene, and are characterized by very  
450 low Ni and Co contents. Their formation is most likely the result of heating during a highly  
451 energetic impact event of short duration that caused the decomposition of troilite, resulting in the  
452 production of S-vapors, which subsequently reacted with FeO in pyroxene to form metal and  
453 silica. The presence of apatite in one of the Fe-metal grains plausibly indicate the reaction of P-  
454 vapors generated by volatilization of P-bearing material (likely mesostasis areas) with Ca  
455 released by pyroxene during its decomposition. The Fe-Ni metal in NWA 11911 has a different  
456 origin and is from a foreign meteoritic source, as indicated by its elevated Ni and Co contents.  
457 This metal was most likely emplaced during an impact event of a metal-bearing impactor with  
458 (4) Vesta, which caused mixing of both its metal with fragments and impact melts of target  
459 basaltic eucrite rocks.

460 We demonstrated in a previous work that NWA 11911 contains evidence of Fe-metasomatic  
461 features engendered by aqueous fluids. In this study, we showed that it also contains records of  
462 secondary alteration by S-vapors, resulting in a sulphide-rich replacement texture engendered by  
463 the decomposition of Fe-rich pyroxene. It also contains clasts originated from an evolved  
464 lithology, displaying symplectic textures formed by the breakdown of metastable pyroxene. The  
465 presence of both types of secondary alteration in the same meteorite, as well as symplectic clasts  
466 makes NWA 11911 an unprecedented eucritic sample providing a window into the complex  
467 magmatic and post-magmatic history of its parent body.

468 In conclusion, our findings from the polymict eucritic breccias Errachidia 002 and NWA  
469 11911 shed light on the important role impacts played in the surface evolution of planetary  
470 bodies like the asteroid (4) Vesta.

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