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GRV 051523: A new eucrite

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Abstract Grove Mountains (GRV) 051523 is a newly identified eucrite, consisting mainly of coarse-grained pyroxene (62.9 vol%) and plagioclase (34.2 vol%), with less abundant opaque minerals (2.7 vol%), minor silica and tiny FeO-rich olivine (Fa_{75}). Coarse-grained pyroxenes show exsolution of augite lamellae in pigeonite or vice versa. Width of most exsolution lamellae in pyroxenes is 1-3 μm. Opaque minerals are mainly chromite, ilmenite and sulfides. The meteorite was heavily shocked, as indicated by breccias and melt veins. Coarse-grained pyroxenes commonly contain abundant tiny or needle-like chromite inclusions with orientation, probably due to heavy shock events. Pyroxenes in various petrographic occurrences exhibit highly homogeneous compositions, indicating that GRV 051523 experienced intense thermal metamorphism in the parent asteroid 4 Vesta. GRV 051523 is classified as Type 5-6. This new eucrite will have additional constraints on chemical composition, magmatic differentiation, multi-stage shock and thermal history of Vesta.

Key words meteorite, eucrite, Antarctic meteorite, thermal metamorphism, Vesta

1 Introduction

Howardites, Eucrites and Diogenites (hereafter HEDs) are the only extraterrestrial basaltic rocks besides the martian and lunar meteorites. HEDs probably came from a same parent body, as the following lines of evidence: (1) whatever major or trace elements exhibit that howardites are the mixture of eucrites and diogenites[1, 2]; (2) The identical O-isotopic compositions of the HEDs ($\Delta^{17}O = -0.25$[3]); (3) HEDs have identical Mn/Fe ratios of both pyroxenes and olivines, which obviously higher than the values of the counterparts in the Earth, Moon and Mars[4, 5]. It is widely accepted that the HEDs probably originate from asteroid 4 Vesta, based on their similar optical reflectance spectral features[6, 7].

Eucrites are further divided into ordinary, surface (or lava-like), cumulate and polymict subtypes[8]. In addition, they experienced complicated thermal metamorphism history, accordingly classified into petrographic type 1 to type 6 based on compositions, textures and metamorphism data of pyroxenes[9]. Based on the petrographic and mineralogical characters of HEDs, a layered-crust model of the HED parent body was proposed, consisting of, from top to bottom, surface eucrites, ordinary eucrites, cumulate eucrites and diogenites[8].

GRV 051523 was found in a moraine west to the middle segment of the Gale Escarpment, Grove Mountains, Antarctica, by Y. T. Lin during the 22nd Chinese Antarctic Research Expedition. Petrographic and mineral chemistry of GRV 051523 was conducted in this study, in order to clarify petrogenesis of this meteorite and to provide additional constraints on evolutional history of the parent body, asteroid-4 Vesta.

2 Sample and experiments

The meteorite was sawn into two halves using a diamond thread saw without water or any other cooling liquid. The smaller part was then embedded in epoxy and cut into several slices using a low-speed diamond saw. One of the slices was made into a polished thin section with a surface of ~ 0.9 cm^2.

Petrographic observations were obtained with optical microscope and scanning electron microscope (SEM) type LEO-1450VP. Mineral chemistry was determined by electron probe microanalyzer (EPMA) type JEOL-JXA 8100, using 15 kV accelerating voltage and 20nA beam current (10 nA for plagioclase). All experiments were carried out at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. Silicates and oxides were used as standards, and the results were treated using the Bence-Albee method. The detection limits are (1σ, wt%): TiO_2 0.03, Al_2O_3 0.01, Cr_2O_3 0.07, MnO 0.07, CaO 0.03, MgO 0.01, Na_2O 0.03, K_2O 0.03. Modal composition of the meteorite was calculated from surface areas of individual minerals in the back-scattered electron (BSE) images.

3 Results

3.1 Petrography

GRV 051523, 0.8 g in weight, has a peanut-like shape with most black fusion crust remained. White breccias of plagioclase can be seen on the exposed surface (Fig. 1).

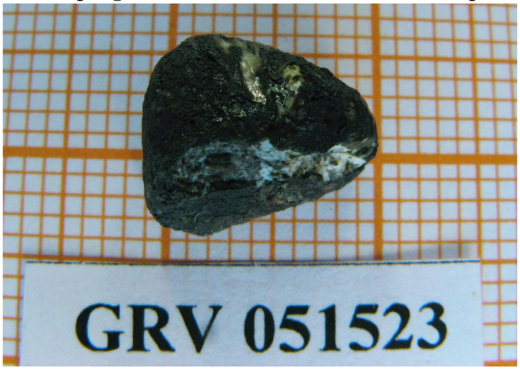

Fig. 1 Photo of GRV 051523. Scale of thin grid is 1 mm.

GRV 051523 mainly consists of pyroxenes (62.9 vol%), plagioclase (34.2 vol%), with less abundant opaque minerals (2.7 vol%), minor silica and tiny fine-grained olivine. The opaque minerals are chromite, ilmenite and sulfides. It has two different textural parts: coarse-grained gabbro texture part (Fig. 2) and fine-grained part recrystallized from shock-induced melt veins (Fig. 3a). The coarse-grained gabbro texture is prevailing, consisting mainly of granular pyroxenes and plagioclase (~1 mm, with a few grains of plagioclase up to 1 mm × 2.3 mm). Tiny inclusions of chromite in pyroxenes are common (Fig. 3b), and show orientation. Many pyroxenes contain exsolved lamellae, with augite lamellae in pigeonite and vise versa (Fig. 3b, 3c). The lamellae are usually 1-3 μm in width, with a few up to 10 μm (Fig. 3d). Fine-grained part (with grain size from 5 to 20 μm) is probably recrystallization of shock-induced melt veins, consisting of pyroxenes, plagioclase, and less abundant opaque minerals (sulfides, chromite and ilmenite) and silica. The euhedral to subhedral silica is rich in this part, and appears to coexist with troilite (Fig. 4a). Olivine is also euhedral to subhedral, with grain size less than 10 μm (Fig. 4a). Pyroxenes in this part rarely show signs of exsolution (Fig. 4a).

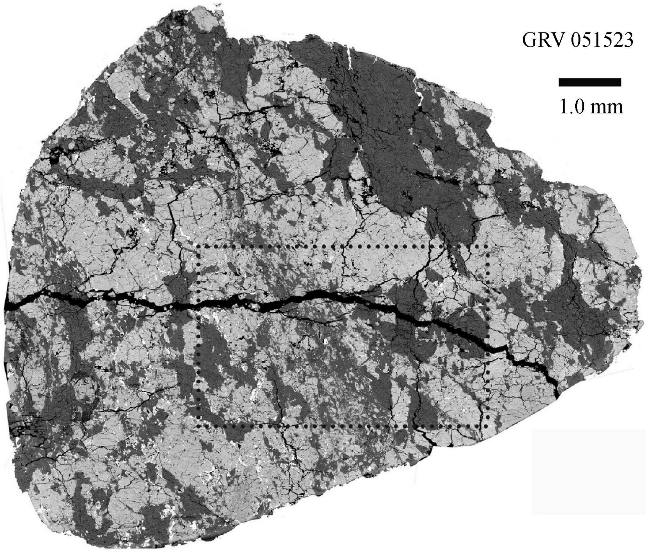

Fig. 2 Back-scattered electron (BSE) image of GRV 051523. The silicates consist of pyroxenes (light grey), plagioclase and silica (dark grey). Bright small grains are ilmenite, chromite and sulfides. The fine-grained part is recrystallization of shock-induced melt vein (the center) with the width up to 1 mm. The dash line region represents the Fig. 3a.

GRV 051523 suffered intense shock modification. Coarse-grained silicates are heavily fractured (Fig. 3a, 3b, 3c, 3d). Shock-induced melt veins are common in this section. The larger one is about 1mm in width. Parts of the matrix of the thin veins are cryptocrystalline. Tiny spherules are chromite.

3.2 *Mineral chemistry*

3.2.1 *Pyroxenes*

Representative analyses of pyroxenes are given in Table 1. No significant variation in chemical composition of pigeonite has been found among the coarse grains ($Wo_{1.7-11.1}$ $Fs_{48.1-59.9}$) and fine grains in the recrystallized melt veins ($Wo_{1.5-2.5}Fs_{56.8-59.2}$). In addition, EPMA profiles conducted on pigeonite across lamella of augite show no significant variations in FeO, MgO and CaO from cores to rims. The average FeO/MnO (wt%) ratio of

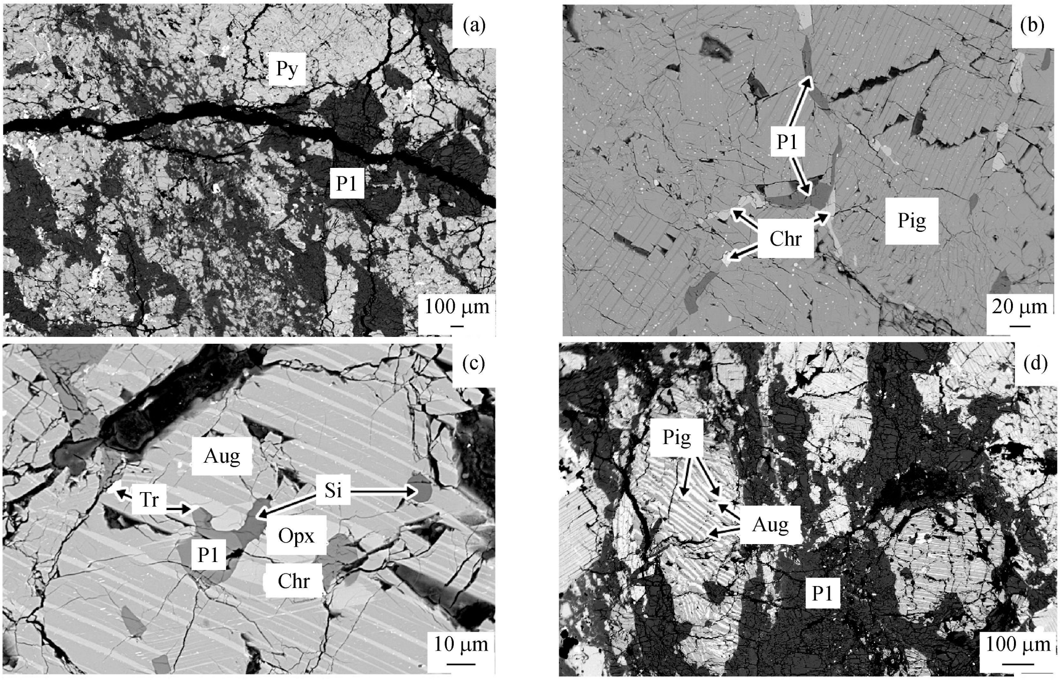

Fig. 3 BSE images of GRV 051523. (a) It shows two different textural parts: fined-grained texture (the left part) and coarse-grained gabbro texture (the right part). The large grains are pyroxenes (Py) and plagioclase (Pl). The bright grains are opaque minerals: chromite (Chr), ilmenite and sulfides. (b) Exsolution lamellae of augite (Aug) in pigeonite (Pig). Light grey grains are chromite. The anhedral plagioclases are interstitial to pyroxenes. Tiny inclusions of chromite in pyroxene are common. (c) Exsolution lamellae of low-Ca pyroxenes (Opx) in augite. Other minerals: SiO_2 (Si); Chromite (Chr); Troilite (Tr). (d) Thick exsolution lamellae of augite in pigeonite (width of lamellae up to 15—20 μm).

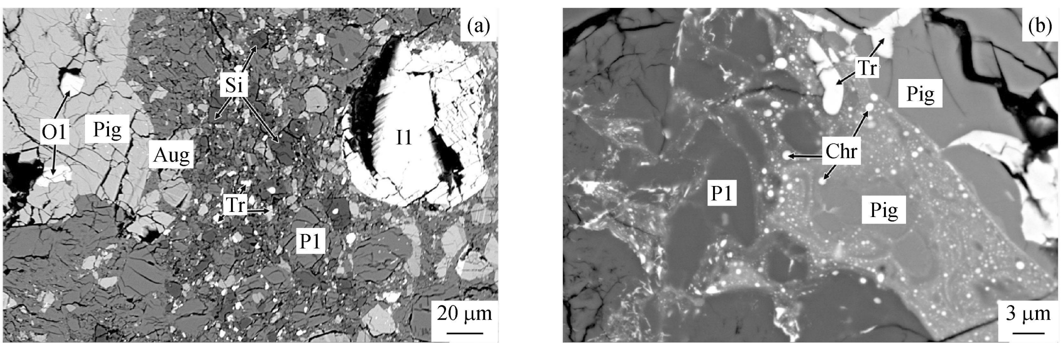

Fig. 4 (a) BSE image of the recrystallization of shock-induced melt vein (a part of the whole vein). Silica systematically appears associated with troilite. Recrystallization of silicate minerals rarely show signs of exsolution. (b) Rapidly cooling of shock-induced melt vein. Parts of the matrix are cryptocrystalline. Tiny spherules are chromite. Abbreviation: Pig (Pigeonite); Aug (Augite); Pl (Plagioclase); Ol (Olivine); Si (SiO_2); Tr (Troilite).

Table 1. Representative electron microprobe analyses of silicate minerals in GRV 051523 (wt%)

	Pigeonite				Augite	Plagioclase				Olivine	
	1′	2#	3°	4°	5	6′	7#	8°	9°	10	11
SiO_2	51.5	51.4	51.1	51.4	51.2	46.5	45.2	46.1	47.5	33.1	32.2
TiO_2	0.10	0.12	0.10	0.13	0.40	n.d	n.d	n.d	n.d	n.d	0.05
Al_2O_3	0.12	0.12	0.16	0.19	0.79	34.6	33.5	34.0	33.7	n.d	n.d
Cr_2O_3	0.11	0.08	0.08	0.08	0.66	n.d	n.d	n.d	n.d	n.d	n.d
FeO	34.6	33.2	34.5	33.5	13.4	0.28	0.04	0.17	0.23	55.7	56.0
MnO	1.28	1.15	1.27	1.14	0.53	n.d	n.d	n.d	n.d	1.48	1.37
MgO	12.5	13.2	12.9	13.8	11.8	n.d	n.d	n.d	n.d	10.3	10.2
CaO	0.62	2.16	0.68	0.68	20.8	18.3	18.5	18.3	17.4	0.04	0.03
Na_2O	0.03	n.d	0.04	n.d	0.04	1.04	0.86	0.98	1.53	n.d	n.d
K_2O	n.d	n.d	n.d	n.d	n.d	0.08	0.05	0.07	0.12	n.d	n.d
Total	100.86	101.37	100.80	100.91	99.57	100.82	98.17	99.59	100.42	100.76	99.89
					Cations per formula						
Si	2.021	2.002	2.010	2.007	1.960	2.125	2.122	2.130	2.171	1.022	1.009
Ti	0.003	0.003	0.003	0.004	0.011	0.000	0.000	0.000	0.000	0.000	0.001
Al	0.006	0.006	0.007	0.009	0.035	1.862	1.853	1.852	1.815	0.000	0.000
Cr	0.003	0.002	0.003	0.002	0.020	0.000	0.001	0.000	0.000	0.000	0.000
Fe	1.134	1.083	1.134	1.093	0.429	0.011	0.002	0.007	0.009	1.439	1.467
Mn	0.042	0.038	0.042	0.038	0.017	0.002	0.000	0.000	0.000	0.039	0.036
Mg	0.733	0.765	0.754	0.802	0.672	0.001	0.000	0.000	0.000	0.476	0.475
Ca	0.026	0.090	0.029	0.028	0.854	0.895	0.931	0.907	0.854	0.001	0.001
Na	0.002	0.000	0.003	0.000	0.003	0.092	0.079	0.088	0.136	0.000	0.000
K	0.000	0.000	0.000	0.001	0.000	0.005	0.003	0.004	0.007	0.000	0.000
Sum	3.973	3.990	3.984	3.984	4.002	4.992	4.992	4.989	4.993	2.977	2.990
Fa/Fs/An	59.9	55.9	59.2	56.8	21.9	90.2	91.9	90.8	85.7	75.1	75.5
Wo/Ab	1.4	4.7	1.5	1.5	43.7	9.3	7.8	8.8	13.6		
En/Or	38.7	39.5	39.3	41.7	34.4	0.5	0.3	0.4	0.7		

Note: n.d not detected; ′ rim; # core; ° minerals in melt vein.

pigeonite (28.3 ± 1.1) plot close to the reference line of HEDs (Fig. 5a).

Only a few of augite were analysed in this study. The composition of augite is $Wo_{43.7}Fs_{21.9}$, with FeO/MnO (wt%) ratio of 25 plotted in the range of HEDs (Fig. 5a). Augite contains more TiO_2, Al_2O_3 and Cr_2O_3, and less FeO and MnO in comparison with the host pigeonite.

3.2.2 Plagioclase

Representative analyses of plagioclase are also listed in Table 1. Coarse-grained plagioclase is homogeneous ($An_{90.2-92.2}Or_{0.2-0.5}$). Only a few grains show slight decrease of CaO from the core ($An_{92.2}$) to the rim ($An_{90.2}$). The tiny grains in recrystallized melt veins have lower CaO ($An_{85.7-90.8}$) relative to the coarse grains. However, all grains of plagioclase in the section are CaO-rich (An > 85.7), and poor in K_2O (Or < 0.7).

3.2.3 Others

The tiny grains of olivine have homogeneous composition, and they contain high FeO (Fa_{75}) and MnO (1.37—1.48 wt%). The ratio of FeO/MnO (wt%) ratio varies from 38 to 41.

4 Discussion

4.1 Classification

The absence of Fe-Ni metal phase and chondrules, and igneous textures (Fig. 2) all indicate that GRV 051523 is a differentiated meteorite. It consists mainly of pyroxenes and plagioclase with minor chromite, ilmenite, troilite and silica minerals, within the range of basalts.

The probable sources for extraterrestrial basalts are the Mars, the Moon and the HED' s parent body (Vesta). Plagioclase of shergottites has lower CaO, within the range of andesine. GRV 99027 and GRV 020090 were classified as lherzolitic shergottite ejected from the Mars[10, 11]. Plagioclases in both meteorites contain An_{42-61} and $An_{36.6-57.3}$, respectively. In comparison, plagioclase of GRV 051523 is more CaO-enriched ($An_{85.7-92.2}$), distinct from those of the martian meteorites. In addition, silicates of GRV 051523 are MnO-rich, with the FeO/MnO ratios of pyroxenes and olivine significantly lower than those of martian meteorites (Fig. 5a, 5b). Although the composition of plagioclase in GRV 051523 is within the range of lunar basalts (An_{85-100}), lunar basalts are poor in MnO with FeO/MnO ratios of pyroxenes and olivine much higher than those of GRV 051523 (Fig. 5a, 5b). On the other hand, the Fe/Mn ratios (24.8—30.5, mol%) of pyroxene and olivine, and anorthite content of plagioclase (85.7—92.2, mol%) of GRV 051523 are plotted in the range of HEDs (Fig. 6).

Table 2 Comparison between GRV 051523 and GRV 99018 in petrography and mineral chemistry

Sample	Pyroxene (vol%)	Plagioclase (vol%)	Opaque minerals (vol%)	Plagioclase An (mol%)	Pyroxenes FeO/MnO (in weight)
GRV 051523	62.9	34.2	2.7	85.7-92.2	~28
GRV 99018	50.5	44.2	5.2	77.4-89	~31

Note: The modal compositions of GRV 051523 refer as[12].

The modal composition, anorthite contents of plagioclase, and FeO/MnO ratios of pyroxenes in GRV 051523 all are similar to GRV 99018 (see Table 2) that was also found in Grove Mountains, Antarctica, and was classified as an ordinary eucrite[12]. However, their differences in modal composition demonstrate that GRV 051523 is not paired with GRV 99018.

4.2 Petrographic type

GRV 051523 has no obvious cumulate texture. The ferrosilite (Fs) contents of low-Ca pyroxenes of GRV 051523 are distinctly higher than those of cumulate eucrite, and plotted in the range of ordinary eucrite (Fig. 7). The fayalite (Fa) content of olivine of GRV

051523 (Fa_{75}) is clearly lower than that of cumulate eucrite (Fa_{98-90}), and also within the range of ordinary eucrite too. Accordingly, GRV 051523 is classified as an ordinary eucrite.

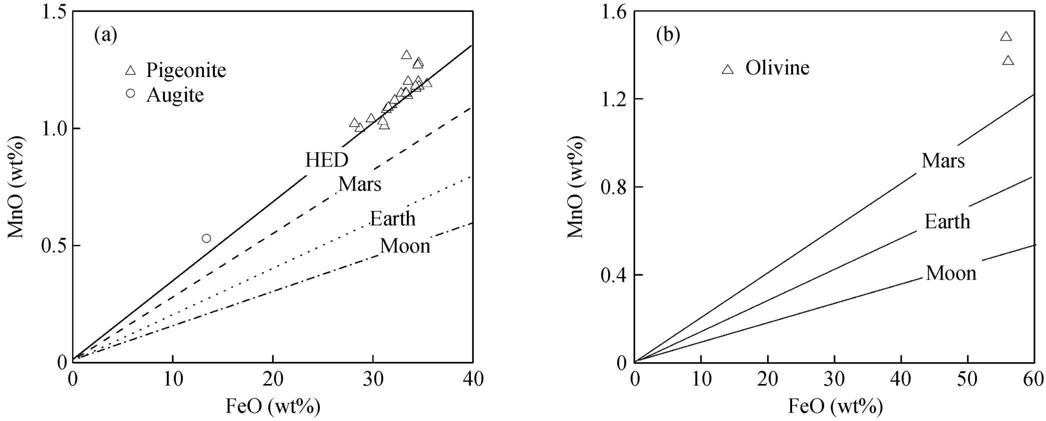

Fig 5 (a) FeO versus MnO plot of pyroxenes in GRV 051523. Both pigeonite and augite plot on the line of HED. Average of FeO/MnO ratios of basaltic pyroxenes from the Earth, Moon, and Mars are shown as references[12]. (b) FeO versus MnO plot of olivine in GRV 051523. The FeO/MnO ratios of olivine of GRV 051523 are obviously below those of the Earth, Mars and Moon[5].

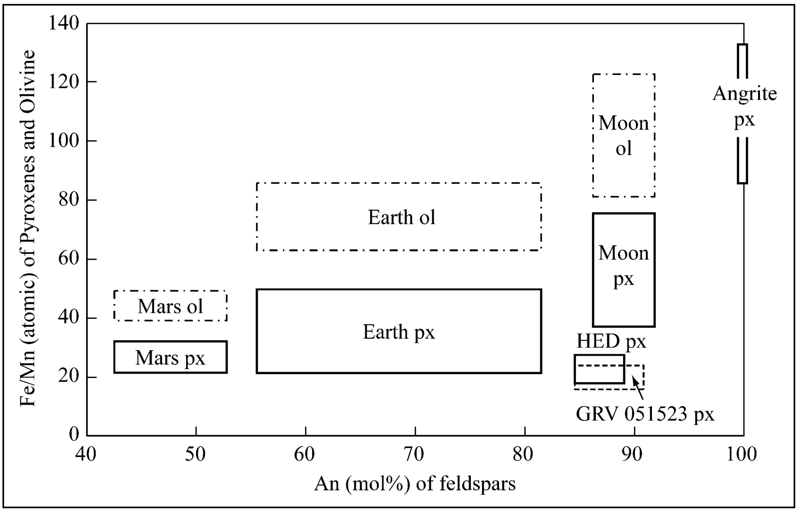

Fig 6 Fe/Mn of pyroxene (px) and olivine (ol) versus An% of plagioclase for planetary basalts. The Fe/Mn of pyroxene and An% of plagioclase of GRV 051523 plot in the range of HED. The compositional ranges represent one standard deviation from the mean values[5].

The homogeneous composition of the coarse-grained host pyroxenes ($mg^{\#}$ ~ 39—47, $mg^{\#} = Mg \times 100/(Mg + Fe)$, atomic), and the wide exsolved lamella of pyroxenes (usually 1—3 μm, a few up to 10 μm, see Fig 3d) in GRV 051523 all demonstrated that this meteorite experienced intense thermal metamorphism ater crystallization. Takeda and Graham (1991) define six types of eucrite based on petrographic criteria and mineral chemistry. Base on this criterion, GRV 051523 can be classified as type 5—6.

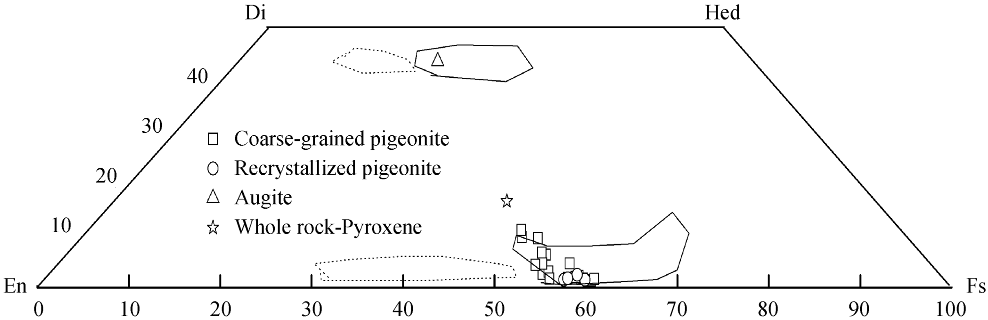

Fig 7 Pyroxenes quadrilateral for GRV 051523. Pigeonites in the coarse-grained breccia and the recrystallized melt vein have similar compositions. Ranges of cumulate eucrites (dotted line) and ordinary eucrite (line) after[8].

4.3 Petrogenesis of GRV 051523

The ordinary eucrite should crystallized at depth between the cumulate and surface types of eucrites according the layered-crust model proposed by Takeda[8]. The original composition of pyroxenes is calculated from the compositions of exsolved lamellae of pigeonite and augite and their volume percentages (Fig 7). Based on the two-pyroxene thermometer[13], the analyses (Fig 7) give the crystallization temperature of 1100℃, which is consistent with that of other ordinary eucrites[14]. After crystallization, the rock experienced slow cooling at a certain depth in order to form the exsolved lamellae of pyroxenes (Fig 3b, c, d). The equilibrium temperature of pyroxenes can be determined from the composition of exsolved lamellae and converted host rock (Fig 7) using the two-pyroxene thermometer, and it is about 600℃. The cooling rate can be calculated from the width and the zoning profile of Ca content (EPMA profile) in exsolved lamellae and host rock[15]. The width of exsolution lamellae of pyroxenes of GRV 051523 is close to that of GRV 99018 and Ibitira, which have a cooling rate 0.02℃/year[12, 16]. So it can conclude that the cooling rate of GRV 051523 is about 0.02℃/year.

The parent body of GRV 051523 suffered intense shock events, producing the brecciation and shock-induced melt veins. Recrystallization of the melt veins indicates that this meteorite was reburied after the main shock event and subsequently cooled slowly. It is noticeable that there are other thin melt veins with opaque spherules in cryptocrystalline matrix (Fig 4b). They indicate another later shock event, followed by a rapid post-impact cooling history. As discussed above, GRV 051523 recorded multiple shock and thermal events of the surface of Vesta. Finally, GRV 051523 was ejected from Vesta into space by another impact event, and fell on the ice sheet of Antarctica.

5 Conclusion

GRV 051523 mainly consists of pyroxenes, plagioclase and with less abundant chromite, ilmenite and sulfides, minor silica and tiny FeO-rich olivine. The calcic plagioclase and high MnO/FeO ratios of Fe-Mg silicates exhibit that GRV 051523 is a new eucrite. The homogeneous composition of the host pyroxenes and the wide exsolved lamella demonstrated that GRV 051523 experienced intense thermal metamorphism (type: 5-6), and it is further classified as an ordinary eucrite.

GRV 051523 probably started to crystallize from liquid at ~1100℃, followed by a slow cooling process after solidification. The equilibrium temperature of pyroxenes is ~600℃ according to the two-pyroxene thermometer, and the cooling rate is about 0.02℃/year. GRV 051523 experienced intense shock events, producing the brecciation and shock-induced melt veins. Recrystallization of the melt veins indicates that this meteorite was reburied after the main impact. Subsequently, GRV 051523 suffered another shock event and formed other thin melt veins. However, after this shock event GRV 051523 was not buried by thick crust, and it may exposed to the surface or ejected from Vesta.

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