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Serra Pelada: the first Amazonian Meteorite fall is a Eucrite (basalt) from Asteroid 4-Vesta

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ABSTRACT

Serra Pelada is the newest Brazilian eucrite and the first recovered fall from Amazonia (State of Pará, Brazil, June 29th 2017). In this paper, we report on its petrography, chemistry, mineralogy and its magnetic properties. Study of four thin sections reveals that the meteorite is brecciated, containing basaltic and gabbroic clasts, as well of recrystallized impact melt, embedded into a fine-medium grained matrix. Chemical analyses suggest that Serra Pelada is a monomict basaltic eucritic breccia, and that the meteorite is a normal member of the HED suite. Our results provide additional geological and compositional information on the lithological diversity of its parent body. The mineralogy of Serra Pelada consists basically of low-Ca pyroxene and high-Ca plagioclase with accessory minerals such as quartz, sulphide (troilite), chromite – ulvöspinel and ilmenite. These data are consistent with the meteorite being an eucrite, a basaltic achondrite and a member of the howardite-eucrite-diogenite (HED) clan of meteorites which most likely are from the crust asteroid 4 Vesta.

Key words: Serra Pelada, meteorite, eucrite, Vesta, Brazilian Meteorite.

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INTRODUCTION

Observed meteorite falls are very important for scientific studies, because the recovered material was not yet subjected to terrestrial weathering.

It is believed that the majority of meteorites are originated on parent bodies in the asteroid belts. Although few specific asteroids have been identified as meteorite sources, there is an association between Vesta (and other asteroids in the Vestoid Family) and the Howardite, Eucrite, Diogenite (HEDs) clan of achondrites (Binzel and Xu 1993). The achondrites are differentiated rocks and were derived from planetary bodies that partially or totally melted. In case of asteroid 4 Vesta, the most likely parent asteroid of the HEDs, this process formed a metallic core, a mafic mantle, and a basaltic crust. This differentiation took place in the very early history of the solar system, and the heat source was short lived ^{26}Al (e.g., Srinivasan et al. 1998, Mittlefehldt et al. 1998, Keil 2002, Mittlefehldt 2005, 2014, 2015).

The eucrites represent volcanic rocks and are subdivided into cumulate and basaltic, based on their pyroxene and plagioclase major-element compositions (McSween et al. 2011). Cumulate eucrites are plutonic rocks (coarse grained equigranular) and primarily composed of anorthite plagioclase (An_{90-96}) and MgO-rich pyroxene (En_{46-65}). Basaltic eucrites are defined by extrusive, i.e., fine- to very fine-grained textures. It is believed that they formed at or near Vesta's surface quickly cooled. They contain pyroxene, FeO-rich ($En_{<46}$), and more sodic plagioclase ($An_{<90}$) than the cumulate (McSween et al. 2011).

Aiming to improve understanding of Vesta magmatic processes, this paper investigates this fresh eucrite fall and describes different textures in the meteorite, as well as the chemical analysis of its minerals.

HISTORY

The Serra Pelada meteorite fell on June 29, 2017 (10:35 local time – UTC-3) at Serra Pelada Village (a famous gold mining location) (5º 57.135'S, 49º 39.238'W), located in the State of Pará, northern Brazil. People reported seeing a fireball in the southeast sky of the state, apparently traveling from NE to SW. A large explosion followed by a series of minors ones was heard in nearby towns such as Marabá, Eldorado dos Carajás and Paraopebas. The inhabitants of these localities thought an airplane had fallen. Using helicopters, the Fire and Police departments searched in vain for the accident.

The students and staff of the Rita Lima Sousa Municipal School who were in the playground witnessed the fall of the rock on the sidewalk, after a sequence of four to six explosions. Also observed were a trail of smoke and a little dust caused by the impact. People went to the impact site and collected fragments of the broken stone leaving only a small impact pit.

A second mass of 5.4 kg was observed to fall and was recovered by an electrician while working at Serra Leste, a Vale do Rio Doce enterprise. This piece was sold to an anonymous buyer. The residents did not realize the importance of the event. They exchanged the fragments among themselves and shared them with local people.

The geologist Marcilio Cardoso Rocha, born at Serra Pelada, was contacted and, suspecting that it was a meteorite, he contacted Dra. Maria Elizabeth Zucolotto (MEZ), the senior author of this paper, who advised him to do some preliminary analyses. Even before Marcílio sent a sample to the Museu Nacional, information about the fall of the meteorite leaked into social medias and shortly dealers went to the place and got many pieces. This event happened while some authors were in the field trying to stablish the strewnfield of Três Irmãos meteorite, which fell in the State of Bahia a month before, which is an unusual fact.

Some of us went to Serra Pelada in order to determine the strewnfield and possibly retrieve other pieces. The task was complicated due to intrinsic difficulties associated with the region, such as the hot weather, a large area covered by forest or high grass and dangerous conditions, such as: find a clandestine gold prospecting, the need to make large amount of withdrawals, and be stopped at a road closed by the Movement of Landless Workers (MST, Movimento dos Trabalhadores Rurais Sem Terra, in Portuguese). The best place for searching was in the Serra Leste enterprise area, but we have not given permission to explore.

The meteorite classification and the name "Serra Pelada" were approved by the Meteorite Nomenclature Committee of the Meteoritical Society N° 106 as a brecciated eucrite.

Figure 1 - A cut section of Serra Pelada meteorite. It shows a typical eucrite with a partial, shiny, black fusion crust and a light colored interior with a brecciated texture. Also visible are some cracks and melt veins. Some clasts show clumps of white blades of plagioclase (size of cube 1 cm).

MATERIALS AND METHODS

Many slices, such as in figure 1, were examined using a stereomicroscope Zeiss Discovery V8. Three polished thin sections were examined microscopically in transmitted and reflected light using a petrographic microscope (Zeiss Axioplan) and minerals in two polished thin sections were analyzed using a JEOL EPMA JXA-8230 Superprobe at LABSONDA/IGEO/UFRJ.

Quantitative analyses of constituent phases we carried out using Wavelength Dispersive Spectrometry (WDS). Beam conditions included an accelerating voltage of 15 KeV, beam current of 20 nA and a spot size of 1 μm for silicates and 20 KeV, for opaque minerals. Well-characterized natural and synthetic phases were used as standards, and corrections for differential matrix effects were made with a ZAF factory supplied procedure. During the study, Energy Dispersive Spectrometer (EDS), back-scattered electrons (BSE) imaging and composition mapping image by WDS were also performed.

Micro-Raman spectroscopy was conducted with a Horiba Jobin Yvon LabRam HR at CETEM (Centro de Tecnologia Mineral). A 632.8 nm laser standardized with a Si chip and a confocal hole of 300. The analyses were performed using a 100 X objective lens on the Raman microscope. The recorded spectra were compared with the RRUFF database for phase identification.

The magnetic data were obtained in a Physical Properties Measurement System, from Quantum Design Inc with Option P500, which uses an extraction technique where the magnetized sample is moved through detection coils. All measurements were performed at room temperature, T=300K, and ramping the magnetic field up to 10 kOe. From the M vs H curve (M = *Magnetization*; H = *Magnetic Field*), we obtained the DC (direct current) susceptibility by angular coefficient of the linear fit up to 500 Oe. The resulting mass susceptibility is calculated according to the mass of each sample.

RESULTS

MORPHOLOGY

As first mentioned in the history of the fall, the first mass of Serra Pelada weighed about 6 kg.

It has been broken and distributed among local inhabitants. The second mass, which weighs 5.4 kg was shaped like a rounded pyramid, having dimensions of 25 x 12.5 x 12 cm and was nearly 80% covered with fusion crust. Many fragments of the first mass showed that most of the samples have a glassy and shiny black fusion crust of about 1.0 mm in thickness. Some pieces also show a crust with flow lines, which are typical for eucrites.

Stereomicroscope examinations of the cut surfaces of various slices, hand specimens and thin sections reveal a heterogeneous, brecciated appearance (Figure 1). The clasts range in size from millimeters to centimeters, in shape from oblate to rectangular, and in texture from very fine to coarse grained. The matrix between the clasts is gray and comprises an overall magmatic intergrowth assemblage of plagioclase and pyroxene.

PETROGRAPHY AND MINERAL CHEMISTRY

Macroscopic analysis of Serra Pelada showed that this meteorite is brecciated in nature (Figs. 1-2) with different kinds of clasts and distinct textural features (Figs. 1-3). Petrographic study revealed different textures of rock fragments embedded within a well-consolidated matrix. Here the textural terminology and abbreviations follow that used by Yamaguchi et al. (1994): **MM** - clastic fine to medium grained matrix (0.05 to 0.1mm) rich in lithic clasts and mineral fragments ranging from 0.05 to 0.8mm. The matrix presents a fragmented aspect and it is difficult to identify the borders of most of the clasts (Fig. 3a); **FX** – very fine grained clast of equigranular subophitic and ophitic textures composed of pyroxenes (<0.07mm) and plagioclase of the same size range (shock melt veins are present within this clast) (Fig. 3b); **CX** - coarse grained

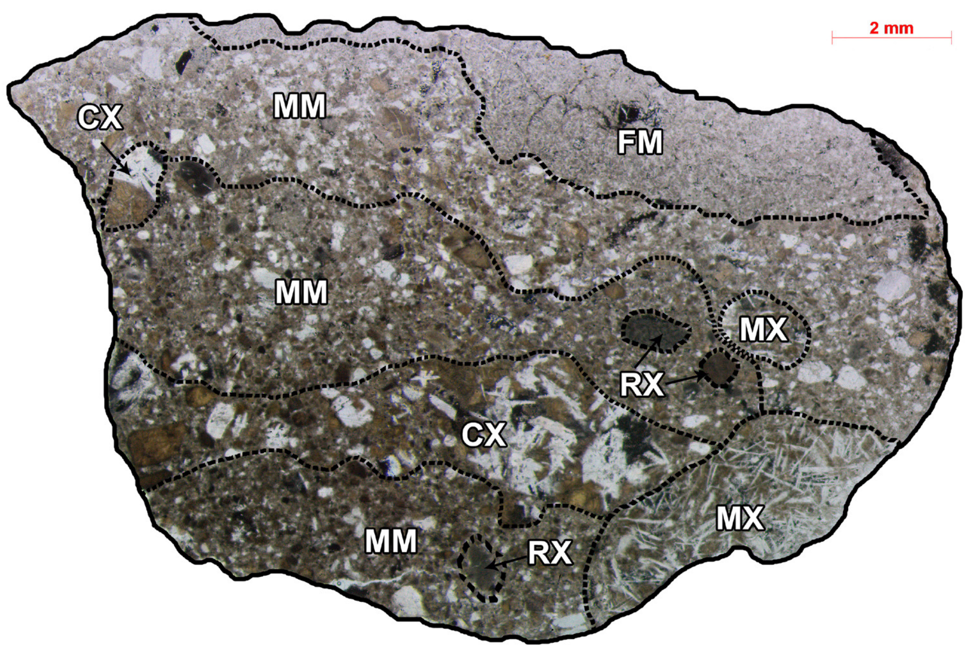

Figure 2 - Picture of a thin section in transmitted light. A variety of light and dark angular clasts range in size from millimeters to centimeters. The lithologies are outlined with dashed lines for better visualization. The matrix and clasts are identified by letters as indicated in the text of the paper. White areas are plagioclase, medium brown areas are clinopyroxene and small black spots are melts and opaque minerals. The abreviations are those presented in figure 3.

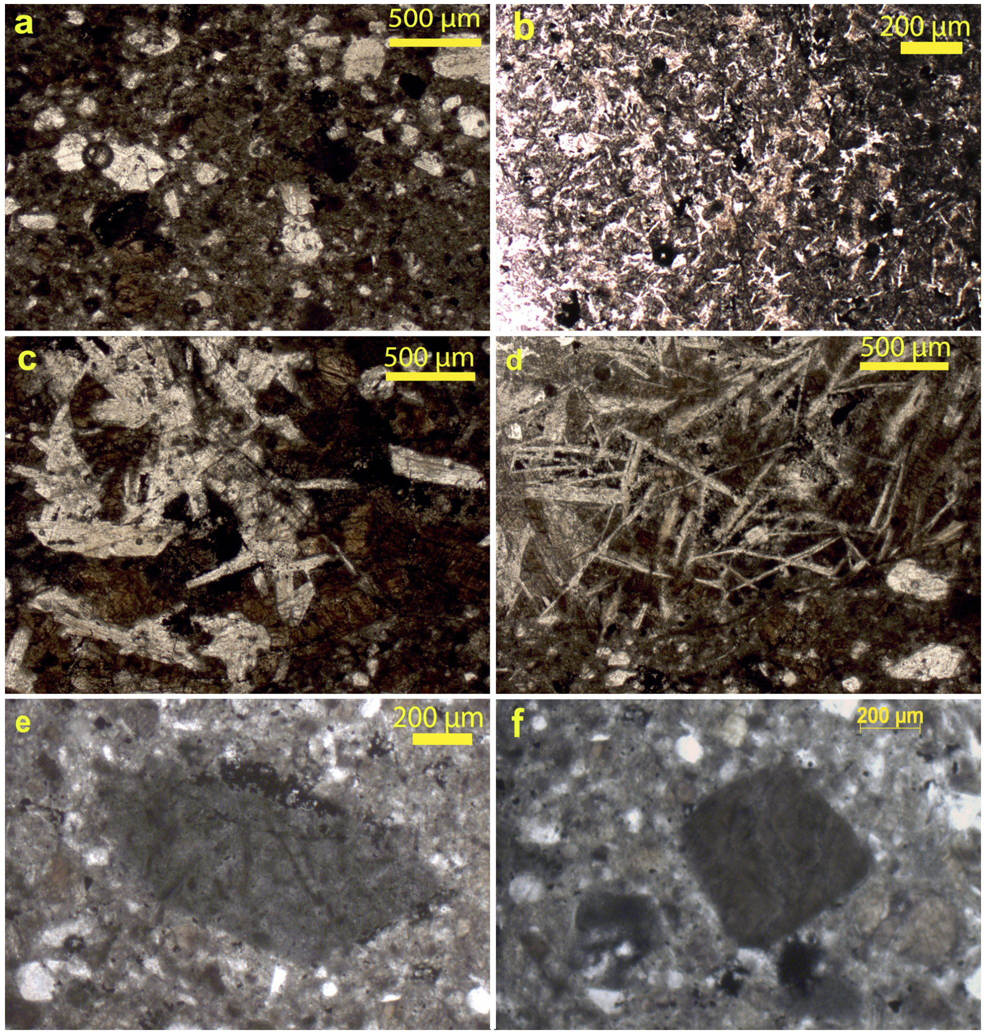

Figure 3 - Transmitted plane polarized light photomicrographs of Serra Pelada showing variability of clast type: (**a**) MM – clastic fine to medium grained matrix , **b**) FX – very fine grained clast , **c**) CX - coarse grained clasts, **d**) MX - Medium grained clasts, **e**-**f**) RX - recrystallized impact melts.

clasts with gabbroic subophitic texture. Fractured anhedral to subhedral pyroxenes (0.6 to 1 mm) show mosaicism and opaque inclusions while plagioclase (0.25 to 0.8 mm) shows undulatory extinction (Fig. 3c); **MX** - Medium grained clasts with subophitic texture. Fractured pyroxene (0.2 to 0.5mm) containing opaque inclusions and mosaicism. Needles of plagioclase ranging from 0.2 to 0.8 mm show undulatory extinction (Fig. 3d); **RX** - recrystallized impact melts (Fig. 3e-f).

Shock features in Serra Pelada are somewhat heterogeneous among the various lithologies. Mostly plagioclase crystals in the entire meteorite preserve their original lath shape and show weak undulatory extinction, although it is difficult to verify in the FX-clasts, due to their small grain size. Many pyroxenes of the CX-clasts are fractured and show mosaic texture. Over some areas, both in the matrix and in the clasts, there are small melt pockets and network-like glassy veins. These veins are composed of mafic glass containing very fine and partly molten minerals. Since no maskelynite is present nor are planar deformation features observed in pyroxenes, the shock stage is estimated to be S3, according to shock metamorphism features proposed for shock classification by Stöffler et al. (1991) and Rubin et al. (1997).

MINERALOGY

The matrix and clasts of Serra Pelada are composed mainly of calcic plagioclase feldspar and clinopyroxenes, with variable composition. Accessory minerals are quartz, apatite and opaque minor phases that include Ni-poor iron, troilite, ilmenite and chromite.

Pyroxene: Pyroxene is identified to be dominantly pigeonite (**MM**: En_{26-29} Wo_{4-29} Fs_{34-61}; **FX**: En_{25-33} Wo_{8-20} Fs_{40-60}; **MX**: $En_{33-39}$$Wo_{7-14}$ Fs_{53-63}; **CX**: En_{29-39} Wo_{7-37} Fs_{33-56}) (Figure 4). Many of these grains in matrix and clasts have exsolved lamellae of augite (Figure 5a, b). The quantitative WDS analysis composition of the pyroxene for each lithology present in Serra Pelada are given in Table I. Some grains have a cloudy appearance due to many tiny opaque mineral inclusions (several microns to submicron dimension) which is a

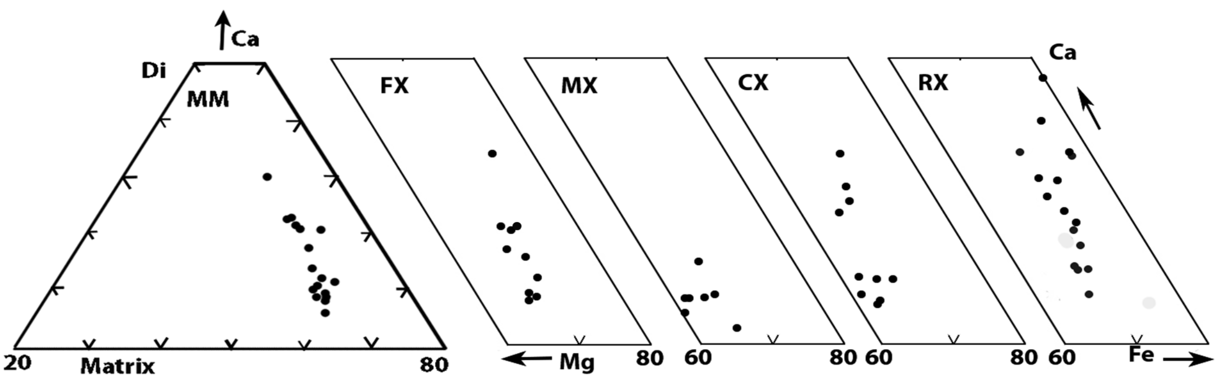

Figure 4 - Pyroxene ternary diagram showing the composition of pyroxene in matrix and clasts in Serra Pelada meteorite.

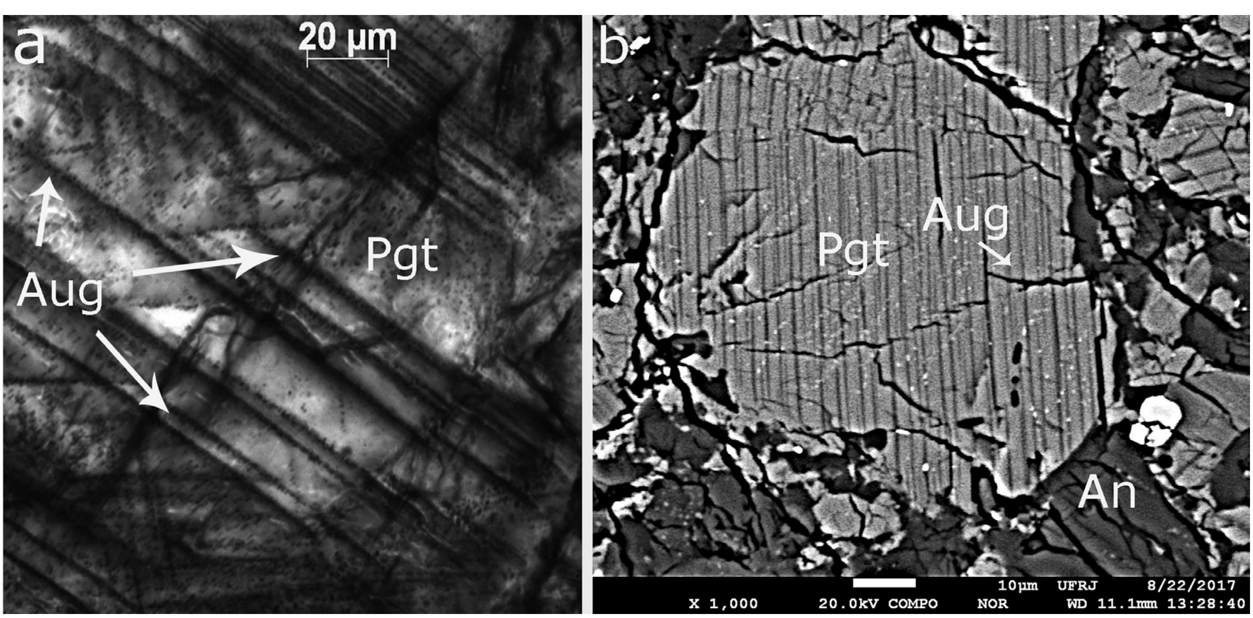

Figure 5 - Pyroxene of Serra Pelada showing pigeonite and augite exsolution lamellae as dark lines. **a**) Transmitted plane polarized light photomicrograph **b**) back scattered electron (BSE) image. Pgt: pigeonite; Aug: augite; An: Anothite-bytownite.

TABLE I
Major and trace element composition of pyroxenes from the different lithologies present in Serra Pelada meteorite. Quantitative WDS analysis in wt. %.

	Al2O3 wt %	MgO wt %	SiO2 wt %	FeO wt %	CaO wt %	TiO2 wt %	Cr2O3 wt %	MnO wt %	CoO wt %	Total wt %
MM fine to medium grained matrix	0.877	10.359	49.054	27.388	10.532	0.282	0.726	0.839	0.000	100.057
	0.400	10.926	48.823	34.428	3.951	0.072	0.310	1.081	0.000	99.991
	0.559	10.697	48.943	33.846	3.906	0.105	1.232	1.031	0.000	100.319
	0.794	10.053	48.809	28.507	9.584	0.277	1.356	0.900	0.004	100.284
	0.227	11.160	49.757	33.646	4.580	0.075	0.154	1.053	0.000	100.652
	0.333	11.056	49.515	33.587	4.684	0.061	0.204	1.089	0.000	100.529
	1.455	10.179	49.614	24.129	14.054	0.177	0.486	0.717	0.000	100.811
	0.597	10.205	48.814	27.766	10.567	0.342	0.524	0.871	0.000	99.686
	0.456	11.198	49.879	33.631	4.520	0.017	0.159	1.072	0.004	100.936
	1.428	9.926	48.154	28.151	10.919	0.231	1.072	0.864	0.000	100.745
FX very fine grained clast	0.879	10.230	49.456	28.723	9.596	0.170	0.339	0.871	0.000	100.264
	0.515	9.898	49.296	29.901	9.312	0.180	0.300	0.929	0.000	100.331
	0.315	9.897	49.371	33.971	5.342	0.131	0.242	1.080	0.000	100.349
	0.494	9.633	49.493	29.953	9.618	0.169	0.430	0.956	0.013	100.759
	3.711	9.428	47.196	30.486	6.636	0.121	0.285	0.949	0.000	98.812
	0.295	10.991	49.771	34.849	3.708	0.104	0.150	1.061	0.000	100.929
	0.554	10.541	49.063	30.275	7.555	0.145	0.557	0.956	0.000	99.646
	9.917	7.209	47.637	20.386	13.097	0.075	0.152	0.658	0.000	99.131
	0.576	10.509	48.544	34.885	3.944	0.140	0.269	1.110	0.000	99.977
	0.446	10.756	48.842	34.609	4.300	0.130	0.791	1.022	0.000	100.896
MX medium grained clasts	0.454	12.913	47.280	32.056	3.684	0.116	0.935	1.012	0.000	98.450
	0.281	12.190	43.190	40.915	1.396	0.017	0.410	1.157	0.000	99.556
	0.464	12.713	49.982	32.267	3.736	0.105	0.477	0.957	0.011	100.712
	0.758	11.129	49.187	31.032	6.645	0.102	0.906	0.970	0.000	100.729
	0.585	12.050	48.675	33.872	3.839	0.105	1.060	1.032	0.000	101.218
	0.807	11.818	47.399	33.622	3.599	0.121	1.239	1.022	0.006	99.633
	0.455	11.213	47.973	33.764	3.980	0.196	0.929	1.066	0.000	99.576
	0.412	13.233	48.727	32.347	2.599	0.101	0.559	1.035	0.000	99.013
	0.412	13.034	49.149	32.408	3.708	0.062	0.415	1.001	0.000	100.189
CX coarse grained clasts	0.708	13.094	49.300	31.585	4.036	0.068	0.787	0.983	0.000	100.561
	0.455	12.411	49.569	33.181	3.191	0.022	0.346	1.058	0.000	100.233
	0.580	12.626	49.658	30.397	5.454	0.084	0.308	1.022	0.000	100.129
	0.378	12.377	49.085	33.360	3.497	0.081	0.625	1.093	0.000	100.496
	1.026	11.571	49.804	31.210	5.152	0.097	0.279	1.021	0.000	100.160
	0.466	11.002	49.501	33.226	5.297	0.087	0.366	1.036	0.000	100.981
	1.205	11.820	49.884	25.598	10.824	0.167	0.450	0.850	0.000	100.798
	0.471	12.405	49.602	33.415	3.033	0.080	0.437	1.081	0.011	100.535
	1.002	11.333	49.846	26.339	10.592	0.118	0.584	0.839	0.000	100.653
	1.186	10.610	49.823	24.595	12.780	0.157	0.441	0.773	0.012	100.377

TABLE I (continuation)

	Al2O3 wt %	MgO wt %	SiO2 wt %	FeO wt %	CaO wt %	TiO2 wt %	Cr2O3 wt %	MnO wt %	CoO wt %	Total wt %
RX recrystallized impact melts	0.854	10.043	48.688	26.711	12.053	0.244	1.042	0.821	0.000	100.456
	6.852	8.558	47.822	25.582	9.647	0.126	0.433	0.816	0.000	99.836
	7.809	7.801	46.940	22.861	11.490	0.242	0.938	0.685	0.003	98.769
	0.809	10.031	48.364	25.225	13.714	0.304	0.843	0.756	0.000	100.046
	4.893	9.485	49.144	28.005	7.867	0.017	0.068	0.887	0.000	100.366
	3.190	9.315	44.911	30.414	7.595	3.980	0.074	0.852	0.000	100.331
	0.317	10.707	48.947	35.324	3.778	0.233	0.300	1.118	0.000	100.724
	5.252	9.946	48.903	30.448	5.706	0.185	0.061	0.937	0.000	101.438
	6.535	9.039	48.544	30.239	5.460	0.095	0.070	0.925	0.000	100.907
	6.473	9.807	48.144	31.850	3.700	0.044	0.059	1.036	0.000	101.113

predominant feature in basaltic eucrites as reported in the literature (e.g. Hutchinson 2004).

Feldspar: Calcic feldspar occurs in all clasts and variable in average composition from An_{81} to $An_{93,}$ which is similar in composition to typical basaltic eucrites of $An_{75\text{-}94}$ (e.g., Mittlefehldt 2015). Many clasts show ophitic/sub-ophitic textures, defined by the presence of subhedral laths of plagioclase feldspars embedded in pyroxene grains. Feldspar also shows a cloudy appearance due many opaque inclusions, also found in the pyroxenes. Most of the feldspar grains have a composition similar to bytownite, whereas a couple of them show anorthite composition (Figure 6). Table II shows the quantitative WDS analysis composition of the plagioclase present in the matrix and clasts.

Accessory minerals: The presence of SiO_2 has been identified as quartz by its Raman spectrum and is a common accessory mineral noticed mostly as inclusions within the plagioclase and also less common within pyroxene. In addition, it occurs in the interstices between plagioclase and pyroxene. Apatite also occurs in minor amounts.

The main opaque phases are troilite and ilmenite, minor amounts of Ni-poor Fe and chromite. There are no systematic differences in chemical compositions between mineral phases in different textural regions. Average composition of ilmenite (TiO_2 = ~51 wt % FeO = ~43 wt %) is consistent with this mineral in other basaltic eucrites (Mayne et al. 2009, Mittlefehldt 2015). Chromite and ulvöspinel occur as accessory phases in sizes up to tens of microns. These chromite/ulvöspinel grains are common minor minerals in basaltic eucrites (Mittlefehldt 2015).

The measurements of the magnetic susceptibility showed that Log χ (10^{-9} m^3/kg) is about 2.9 and the density is 2.77 g/cm^3.

DISCUSSION

Petrographic properties and mineral chemistry data of Serra Pelada are typical of eucrites of the HED clan and confirm its origin from asteroid 4 Vesta (Figure 7 and Table III). It is a monomict breccia with lithic and mineral clasts set in a matrix of fine to medium-grained mineral fragments. As observed in most of the known eucrites, there are no systematic differences in chemical compositions of minerals among different textural regions.

The chemical data are broadly consistent with literature values for noncumulate eucrites, although TiO_2 values are lower than those presented by Barrat et al. (2000) (Figure 8).

As indicated in figure 4, pyroxene compositions of matrix and clasts plot along a single tie line in the pyroxene quadrilateral regardless of the texture.

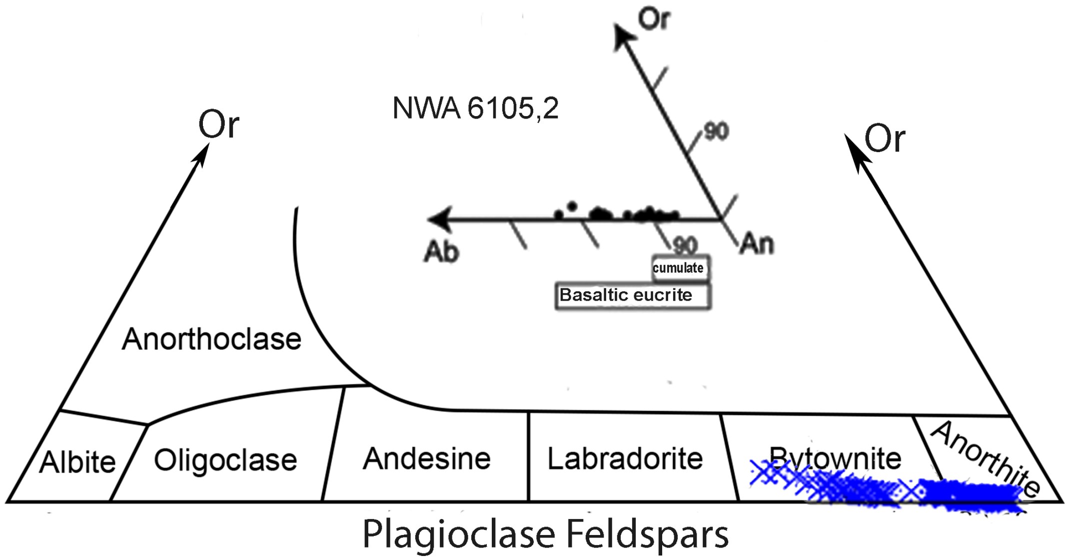

Figure 6 - An-Ab-Or ternary diagram depicting the plagioclase compositions in Serra Pelada compared with NWA 6105,2 (McSween et al. 2011).

TABLE II
Major and trace element composition of plagioclase from the different lithologies present in Serra Pelada meteorite. Quantitative WDS analysis in wt. %.

	Na2O wt %	Al2O3 wt %	SiO2 wt %	MgO wt %	CaO wt %	FeO wt %	K2O wt %	TiO2 wt %	MnO wt %	Cr2O3 wt %	Total wt %
MM fine to medium grained matrix	0.537	36.256	44.002	0.043	18.772	0.354	0.063	0.000	0.000	0.000	100.027
	0.853	35.018	45.495	0.001	17.913	0.277	0.091	0.000	0.000	0.010	99.658
	0.782	35.372	45.533	0.022	17.799	0.248	0.053	0.000	0.000	0.014	99.823
	2.874	31.056	51.160	0.068	13.957	0.292	0.575	0.022	0.000	0.000	100.004
	0.746	35.949	44.734	0.009	18.346	0.233	0.054	0.007	0.000	0.004	100.082
	0.575	36.336	44.281	0.032	18.708	0.153	0.072	0.020	0.049	0.000	100.226
	0.816	35.573	45.553	0.018	17.899	0.151	0.099	0.011	0.000	0.011	100.131
	0.771	35.283	45.584	0.129	17.847	0.480	0.082	0.000	0.032	0.002	100.210
	1.945	33.495	47.150	0.264	16.610	0.857	0.164	0.054	0.042	0.017	100.598
	1.201	34.641	46.980	0.016	16.750	0.367	0.180	0.038	0.018	0.005	100.196
FX very fine grained clast	1.195	33.570	47.835	0.088	16.363	0.584	0.160	0.000	0.000	0.019	99.814
	1.071	34.198	46.858	0.057	16.706	0.418	0.142	0.011	0.000	0.036	99.497
	1.869	33.548	46.954	0.145	15.988	0.988	0.200	0.000	0.000	0.016	99.708
	1.789	34.077	47.419	0.059	16.498	0.351	0.147	0.042	0.048	0.000	100.430
	0.928	31.495	50.456	0.036	15.745	0.287	0.096	0.035	0.000	0.000	99.078
	0.975	35.125	46.282	0.033	17.432	0.337	0.065	0.003	0.011	0.019	100.282
	0.900	34.386	45.765	0.315	17.037	1.627	0.041	0.073	0.062	0.026	100.232
	0.864	34.586	46.358	0.096	17.370	0.597	0.122	0.000	0.004	0.006	100.003
	0.044	0.691	97.472	0.020	0.250	0.222	0.027	0.091	0.004	0.003	98.824
	0.907	34.638	46.260	0.119	17.446	0.366	0.109	0.050	0.029	0.000	99.924

TABLE II (continuation)

	Na2O wt %	Al2O3 wt %	SiO2 wt %	MgO wt %	CaO wt %	FeO wt %	K2O wt %	TiO2 wt %	MnO wt %	Cr2O3 wt %	Total wt %
MX medium grained clasts	1.390	33.224	47.740	0.278	16.024	0.801	0.208	0.023	0.020	0.000	99.708
	2.045	34.001	47.409	0.090	16.299	0.629	0.193	0.000	0.002	0.014	100.682
	1.832	34.265	47.041	0.157	16.662	0.657	0.142	0.000	0.000	0.000	100.756
	1.182	34.312	47.137	0.049	16.818	0.409	0.160	0.002	0.077	0.000	100.146
	0.962	34.971	46.015	0.035	17.169	0.248	0.088	0.000	0.066	0.000	99.554
	0.608	35.928	44.611	0.101	17.999	0.555	0.101	0.000	0.032	0.000	99.935
	1.194	33.533	47.054	0.219	16.422	1.018	0.204	0.004	0.003	0.025	99.676
	1.082	35.015	46.434	0.022	17.152	0.312	0.134	0.019	0.000	0.009	100.179
	2.354	33.835	47.801	0.104	15.766	0.664	0.250	0.014	0.031	0.000	100.819
	1.177	34.362	46.802	0.085	16.467	0.466	0.196	0.001	0.019	0.019	99.594
CX coarse grained clasts	0.817	35.385	45.087	0.013	17.707	0.223	0.079	0.000	0.006	0.000	99.317
	1.157	34.381	46.767	0.100	16.847	0.243	0.177	0.003	0.000	0.000	99.675
	0.732	35.943	44.557	0.037	18.064	0.179	0.057	0.006	0.004	0.024	99.603
	2.031	34.177	47.224	0.104	16.403	0.431	0.190	0.017	0.000	0.000	100.577
	0.812	35.704	45.736	0.022	17.724	0.124	0.122	0.022	0.000	0.020	100.286
	0.846	35.823	44.982	0.000	17.960	0.203	0.070	0.015	0.000	0.009	99.908
	0.945	35.606	45.651	0.011	17.436	0.208	0.127	0.000	0.037	0.000	100.021
	1.079	34.492	46.201	0.206	16.932	1.095	0.118	0.000	0.064	0.010	100.197
	0.759	35.992	44.958	0.027	18.022	0.196	0.083	0.022	0.000	0.000	100.059
	1.871	34.350	47.319	0.025	16.558	0.250	0.184	0.011	0.001	0.000	100.569
RX recrystallized impact melts	0.984	34.893	46.716	0.048	16.433	0.751	0.145	0.013	0.017	0.004	100.004
	0.647	31.417	50.526	0.010	15.762	1.299	0.077	0.105	0.039	0.000	99.882
	0.531	24.776	60.393	0.005	12.280	2.714	0.073	0.141	0.000	0.007	100.920
	1.404	29.591	50.363	0.650	13.824	2.986	0.329	0.015	0.079	0.000	99.241
	2.087	30.185	50.990	0.459	14.281	2.174	0.360	0.009	0.000	0.016	100.561
	2.164	33.428	47.333	0.225	15.602	1.199	0.318	0.038	0.000	0.001	100.308
	1.132	31.397	49.133	0.184	15.518	1.405	0.211	0.059	0.112	0.020	99.171
	0.515	18.274	66.710	0.413	9.326	3.376	0.101	0.189	0.070	0.027	99.001
	1.292	31.458	49.068	0.289	14.998	1.862	0.267	0.027	0.088	0.038	99.387
	2.501	31.211	51.415	0.029	14.334	0.734	0.477	0.033	0.032	0.001	100.767

TABLE III

Comparing Serra Pelada pyroxene and plagioclase data with others planetary basalts. These literature data were taken from Papike et al. (2003). Pyx: pyxroxene; An: Anothite-bytownite.

Earth		Moon		Mars		4-Vesta		Serra Pelada	
Pyx Fe/Mn	An %	Pyx Fe/Mn	An %	Pyx Fe/Mn	An %	Pyx Fe/Mn	An %	Pyx Fe/Mn	An %
x = 40	x = 69	x = 62	x = 89	x = 32	x = 49	x = 30	x = 87	x = 32	x = 89
sd = 11	sd = 12	sd = 18	sd = 3	sd = 6	sd = 5	sd = 2	sd = 2	sd = 2	sd = 5
N = 513	N = 474	N = 37	N = 243	N = 33	N = 39	N = 38	N = 35	N = 65	N = 62

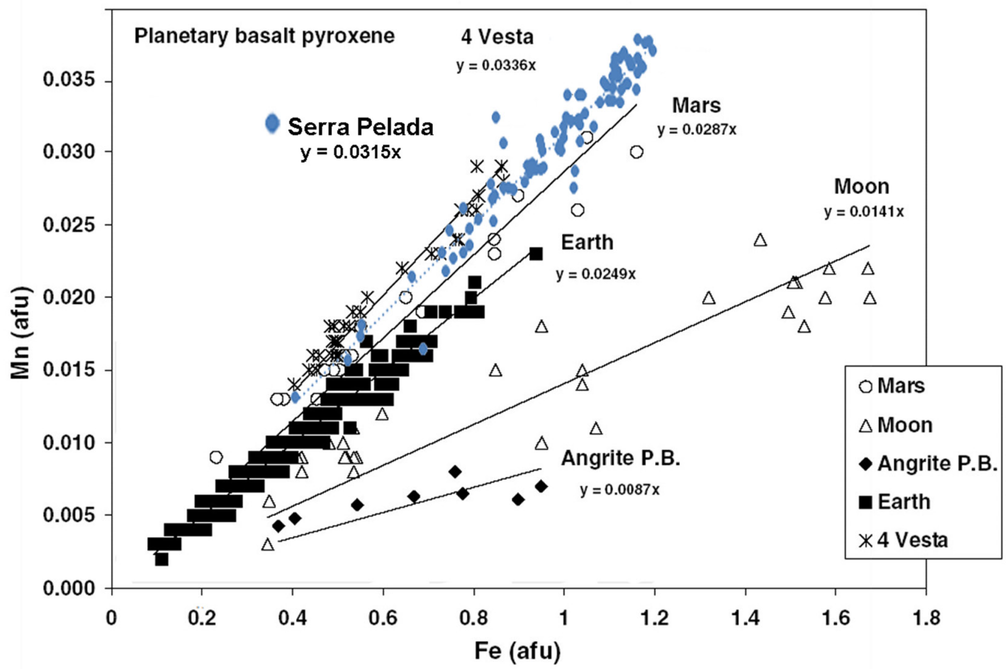

Figure 7 - Fe vs. Mn per 6-oxygen formula unit for pyroxene from planetary basalts, modified from Papike et al. (2003). The angular coefficient of Serra Pelada fits well with an origin from asteroid 4 Vesta.

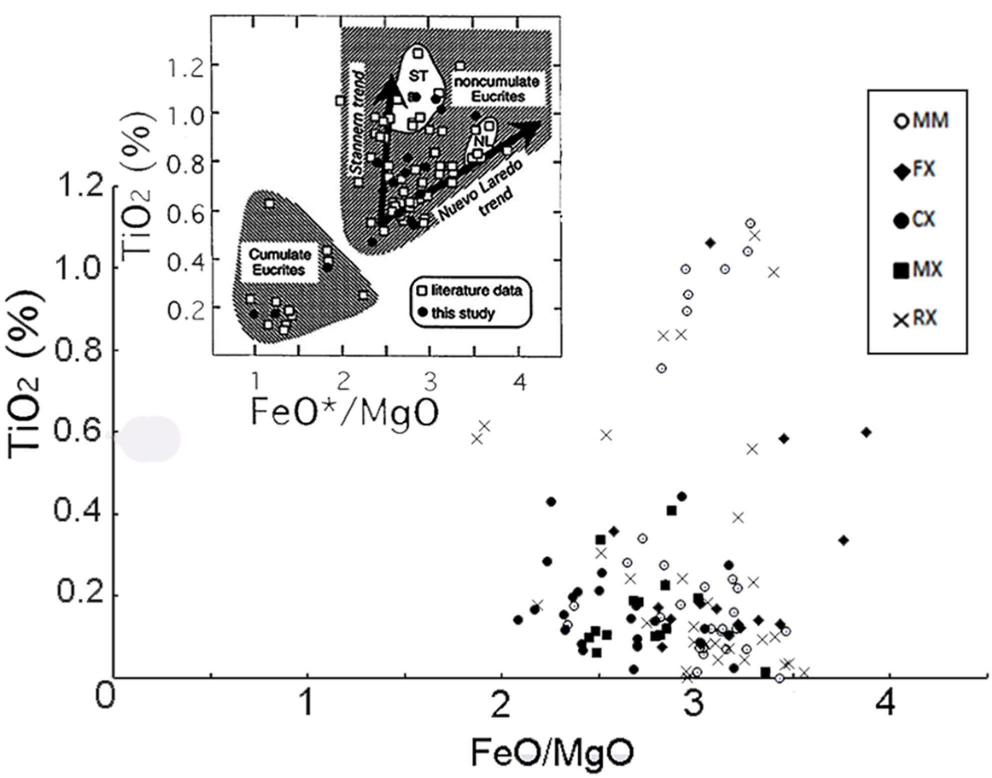

Figure 8 - Plot of FeO/MgO vs. TiO_2 for Serra Pelada eucrite, showing different ratios for each clast and matrix. This plot is compared with literature data taken from Barrat et al. (2000), the small figure inside the graph.

However, the Mg concentration of pyroxene in the crystalline MX clasts is slightly higher than in other regions.

The Mn-Fe correlation of pyroxene in figure 7 shows that Serra Pelada has a slope of 0.03115, which is close to 0.0336 value found by Papike et al. (2003) for 4 Vesta (but in fact this is an average trend line between diogenites and eucrites). Primitive bodies in the solar system can have different Fe/Mn ratios in their silicate minerals as a consequence of volatility and oxidation state (Figure 9). The manganese enrichments in bodies such as 4 Vesta and Mars compared with the Earth and Moon have also been noted by Drake et al. (1989). These observations suggest that the Mn/Fe ratio of materials can be used as a fingerprint of planetary provenance (Papike 1998).

The different textures among the CX, MX and FX clasts may be due to the location within different lava units. Comparing the percentage of TiO_2 and FeO/MgO ratio of Serra Pelada with the literature (Figure 8), the Serra Pelada FeO/MgO ratio is located in the region close to that of noncumulate eucrites (Barrat et al. 2000), although the TiO_2wt% is lower than expected for these meteorites.

In our analysis, the amount of elemental titanium in chromite (ulvöspinel) is higher than in other eucrites, which may be linked to different degrees of oxidation. The reduced chrome and titanium in oxidizing conditions could be more abundant during the formation (Bunch and Keil 1971). High-Ti chromite grains are also a typical feature of highly metamorphosed eucrites due to the decomposition of spinel (Yamaguchi et al. 2001).

Using plagioclase as a classification method (Table III), the values for Serra Pelada, agree with those of 4 Vesta (Papike et al. 2003). Our results

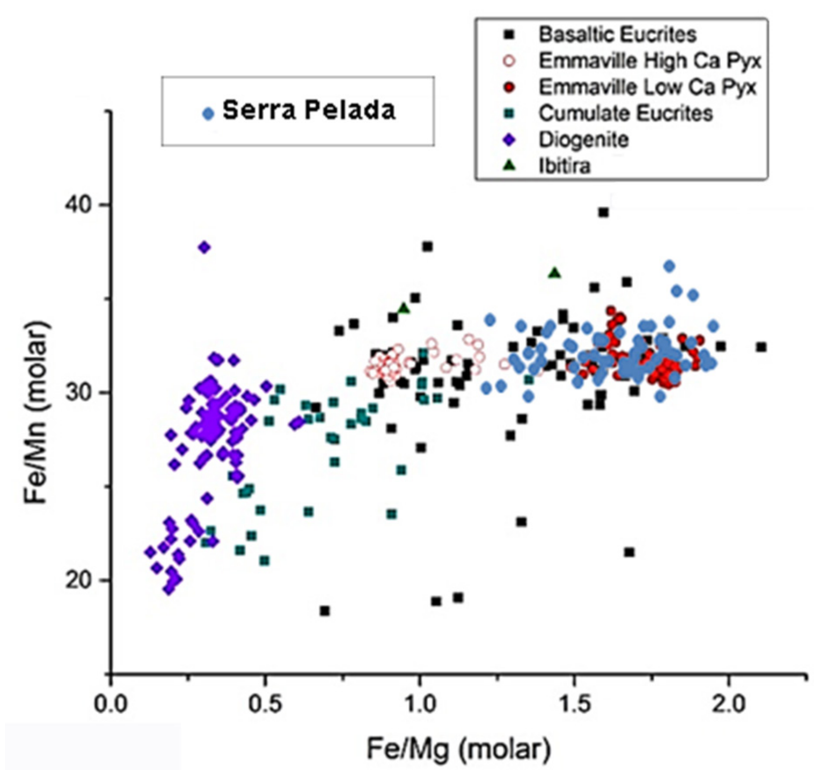

Figure 9 - Pyroxene Fe/Mg vs. Fe/Mn diagram. Basaltic eucrite, cumulate eucrite, diogenite and Ibitira data taken from Barret et al. (2015). Serra Pelada fits well within the low Ca basaltic eucrites.

confirm that this can also be a useful method for planetary origin sorting.

Pyroxenes and plagioclases in the CX- and FX-clasts have a cloudy appearance. This feature has been reported by Harlow and Klimentidis (1980) to be a predominant feature of basaltic eucrites, although there are variations for each meteorite. The observed cloudy appearance can be explained by metamorphism without recrystallization. As a result, iron in plagioclase exsolved into blebs and rods of iron oxides (Harlow and Klimentidis 1980).

Just as chondritic meteorites can be classified on the basis of thermal metamosphism, the eucrites also are classified into six exsolved types by Takeda and Graham (1991). These types reflect the cooling history of the eucrites, which is controlled by its depth in the parent body. The Serra Pelada fits well with type 5 mainly because of: 1) homogeneous chemical composition; 2) occurrence of cloudy pyroxene; 3) exsolution lamellae of augite in pigeonite; 4) recrystallized matrix, and 5) absence of inverted orthopyroxene.

The magnetic susceptibility Log χ (10^{-9} m^3/kg) about 2.9 corresponds well within the level of confidence to eucrite meteorites in the alignment chart given by Folco et al. (2006), revealing in this way, that it is a “magmatic” meteorite that comes from the asteroid belt.

Dawn’s mission, which covered a large fraction of Vesta’ surface, shows that the mineralogy is consistent with howardite-eucrite-diogenite (HED) meteorites (McSween et al. 2013). The howardite regolithic soil exhibits variable proportions of eucrite and diogenite material (De Sanctis et al. 2012, Ammannito et al. 2013). The study of HEDs allows a better understanding of the early differentiation of small bodies in the solar system subjected to low-gravity environments and post crystallization effects of impact metamorphism (Jasmeet et al. 2013).

CONCLUSIONS

Some remarkable attributes observed in Serra Pelada meteorite provide mineralogical and compositional information on diverse fragments. On the basis of petrography and mineral chemistry, we conclude that Serra Pelada is a basaltic monomict eucrite of Type 5 S3. It contains lithic and mineral clasts (mostly different varieties) indicating that the original igneous lithologies were subjected to post-crystallization thermal processing. These results help understand the surface of Vesta, covered by debris that resulted from impacts.

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