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A DETAILED MINERALOGICAL AND ISOTOPIC STUDY OF THE HISTORIC MONOMICT EUCRITE

PADVARNINKAI. T. J. Barrett¹, A. J. King^{2,1}, G. Degli-Alessandrini, E. Humphreys-Williams², B. Schmidt², R. C. Greenwood¹, F. A. J. Abernethy¹, M. Anand^{1,2}, E. Rudnickaite³. ¹School of Physical Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK (E-mail: thomas.barrett@open.ac.uk), ²Department of Earth Sciences, Natural History Museum, London, SW7 5BD, UK, ³Department of Geology and Mineralogy, Museum of Geology of Vilnius University, M.K. Čiurlionio str. 21/27, Vilnius 03101, Lithuania.

Introduction: Eucrites are differentiated achondrites that share a common provenance with howardites and diogenites, commonly referred to as the HED meteorites. The HEDs constitute the largest group of achondrites available in the meteorite collection from a differentiated asteroid, likely 4 Vesta [1-2]. As such, samples from this group can provide unparalleled insight into the differentiation processes that occurred on small airless bodies early in the Solar System history.

Hypervelocity collisions and impacts are important Solar System processes and their records are preserved as shock metamorphic effects in many meteorites [3]. These processes result in deformation features in rocks such as brecciation, melt vein/pocket formation, and/or high-pressure and high-temperature polymorphs (e.g., [3-4]).

Padvarninkai is a monomict eucrite fall originally classified as a shergottite based on the presence of maskelynite [5]; however, its chemical and oxygen isotopic composition later confirmed it to be a eucrite [6-7]. Given its strong shock features, it is considered to be the most shocked eucrite in the meteorite collection (42-60 GPa [8]).

Currently, there are few descriptions of Padvarninkai in the literature [6, 9-11], with most work focusing solely on the chronology of the sample [12-13]. In this study, a comprehensive examination of its mineralogy and petrology, bulk-rock major, minor and trace element abundances, and isotopic composition (C, O) is presented.

Methods: Analyses were conducted on two polished thin sections prepared at The Open University (OU) from an 18.95 g piece of Padvarninkai provided by Vilnius University Department of Geology and Mineralogy, as well as a polished thin section from the Smithsonian Institute (USNM 5946).

Each thin section was examined at the OU using a Quanta 3D FIB-SEM fitted with an Oxford Instrument INCA energy dispersive X-ray detector. Quantitative mineral data were acquired at the OU using a Cameca SX100 EPMA. Major silicates were analysed using a 10 µm spot and an accelerating voltage of 20 kV and a beam current of 20 nA. For apatite, beam conditions were similar to those recommended by [14].

Bulk-rock major, minor, and trace element data were determined using ICP-OES and ICP-MS at the

Imaging and Analysis Centre (IAC) at the Natural History Museum (NHM), London. The whole-rock carbon and nitrogen isotopic composition of Padvarninkai was measured using the Finesse stepped combustion gas extraction mass spectrometry system [15], while oxygen isotopes were measured using the laser-assisted fluorination system [16], both at the OU.

Results and Discussion: Mineralogy and Petrology: Hand specimen observations of a fragment of Padvarninkai highlight a fine-grained light-grey rock with some additional lighter-colored, coarser grains present within the sample, along with schlieren — irregular streaks with a different composition to surrounding material. Parts of the sample are stained to a pale tan-orange color, whilst other regions appear to be rusted. The fusion crust displays small regmaglypts and some abrasion as well as heterogeneity, with some regions more shiny and glassy in texture and others more crystalline.

Padvarninkai is a monomict eucrite consisting of a fine- to coarse-grained unbrecciated lithology and impact melt veins. Pyroxene and plagioclase grains are typically ~10-60 µm in the longest dimension; however, some regions are noticeably coarser with grains up to ~500 µm in length. Pyroxene is severely fractured and mosaicked type 5 pigeonite ($\text{En}_{38}\text{Fs}_{54}\text{Wo}_8$; Mg# 41.7) and, despite the shock textures, an igneous texture is still well preserved, displaying exsolution lamellae at a variety of scales (6-22 µm; $\text{En}_{32}\text{Fs}_{29}\text{Wo}_{39}$; Mg# 52.5) (Fig. 1).

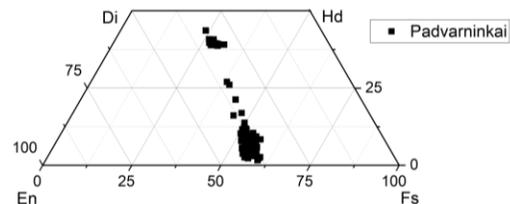


Figure 1: Truncated pyroxene ternary of Padvarninkai data. Plagioclase (bytownite; $\text{An}_{88.4}\text{Ab}_{11.2}\text{Or}_{0.4}$) is mostly ophitic in texture and, depending on the proximity of grains to impact melt veins, either partially or totally converted to maskelynite. Apatite (~50-100 µm in the longest dimension) are fluorine-rich, subhedral to anhedral and heavily fractured. The chemistries of these minerals are all broadly consistent with a basaltic eu-

crite classification [17], although the pyroxene Mg# is slightly higher than average.

Recently, Miyahara [18] described in detail the shock-melt veins and high-pressure polymorphs entrained within the shock-melt zones and suggested that Padvarninkai suffered two impact events at lower shock pressures (22-27 GPa and 2-13 GPa). Our observations, however, do not correlate with the lower shock estimates. In both plagioclase and pyroxene, planar deformation features can be observed in plane polarized light. Electron Backscatter Diffraction (EBSD) maps indicate some mosaicism of pyroxene grains surrounding the apatite [19]. Apatite grains in these maps reveal extensive subgrain formation, potentially recrystallisation, and a large spread in crystallographic orientations (up to $\sim 60^\circ$) [19]. These features are more consistent with an M-S4/5 rating at the lower end of original pressure estimate for Padvarninkai.

Bulk-rock Analyses: For the majority of major element data acquired in this study, Padvarninkai displays similarities with basaltic eucrite values. Magnesium, however, is elevated, and both P and K are towards the lower end of the basaltic eucrite range. The elevated Mg content of Padvarninkai could indicate that it is a particularly primitive eucrite. Compared to basaltic eucrites, Padvarninkai also has a high Ni content and slightly low U content. This high Ni content could be evidence of meteorite impactor contamination. The overall REE pattern for Padvarninkai is flat (~ 10 - $12 \times$ CI), similar to other basaltic eucrites, and clearly resolvable from the Stannern Trend (Fig. 2). As such, it can be considered part of the Main Group of eucrites.

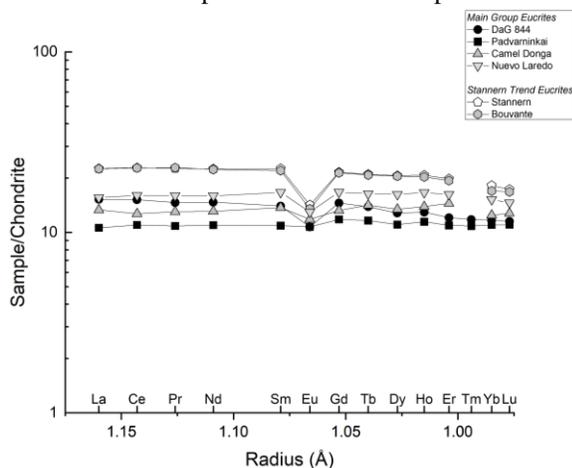


Figure 2: REE pattern of Padvarninkai along with representative eucrites. Eucrite data from [20-21] and the reference chondrite is from [22].

Isotopic Analyses: Unfortunately, the nitrogen results did not exceed blank levels by any meaningful level. In the majority of carbon release steps, the release of carbon was not significantly above the blank.

The exception was a large release (37.5 ppm) at 600 $^\circ\text{C}$, which had a $\delta^{13}\text{C}$ value of $-5.9 \pm 2.0 \text{ ‰}$, within the terrestrial soil carbonate $\delta^{13}\text{C}$ range of -10 ‰ to $+5 \text{ ‰}$ [23]. The abundance and isotopic composition of carbon is also outside the typical range observed for eucrites ($\sim -25 \text{ ‰}$ and $\sim 19 \text{ ppm}$ [24]); however, the isotopic composition is similar to the howardite Kapoeta (-6 ‰), albeit with lower carbon contents [24]. It has been suggested that Kapoeta could have been contaminated with minor amounts of CM or CR material to alter its $\delta^{13}\text{C}$ value [24]. As Padvarninkai has experienced significant impact deformation and possible impact contamination (as evidenced by the high Ni content), this could potentially be an option here too, although terrestrial contamination cannot be ruled out currently.

Oxygen isotope analyses of powder taken from a fresh portion of Padvarninkai ($\delta^{17}\text{O}$ $1.696 \pm 0.122 \text{ ‰}$; $\delta^{18}\text{O}$ $3.705 \pm 0.181 \text{ ‰}$; $\Delta^{17}\text{O}$ $-0.245 \pm 0.280 \text{ ‰}$), all 2σ) closely match those previously obtained [7]. Analysis of the orange and rusted areas of Padvarninkai to ascertain the potential level of terrestrial contamination of this eucrite fall will be conducted in the near future.

Conclusions: Given the monomict and likely primitive nature of Padvarninkai, this sample has the potential to provide important additional insights into the reservoirs and processes prevalent in early Vesta's history and if/how these could have been effected by the significant shock pressures this sample has experienced (e.g., [25]).

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