Lieksa-4: a P-rich iron meteorite from Lieksa

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Lieksa-4 is an iron meteorite find from Löpönvaara, Lieksa. The meteorite consists of approximately 84 wt% Fe, 11 wt% Ni, and 4 wt% P. Trace elements Ga, Ge, Au, and Ir occur in low abundances. The sample consists mainly of rounded kamacite granules in a schreibersite-matrix. Troilite occurs in the matrix in low abundances. Moreover, Neumann deformation lines were detected. The optical, mineralogical, and geochemical features indicate that Lieksa-4 is an anomalous iron meteorite.

Keywords: iron meteorite, anomalous iron meteorite, LA-SC-ICPMS, FE-SEM, XRD

1. Introduction

A total of 14 meteorites have been found in Finland so far (Kuva et al., 2017). Two of these have been investigated in more detail, the Haverö ureilite (e.g., Neuvonen et al., 1972) and the Bjurböle chondrite (Maksimova et al., 2021). The latest meteorite find in Finland is the Lieksa iron meteorite (Kuva et al., 2017). Both the Lieksa meteorite and Lieksa-4 were discovered from the same area together with 3 other suspected meteorites (Moilanen, 2018). Lieksa-4 was found by Pekka Kokko, and the sample was suspected of being a meteorite. However, the preliminary investigation revealed that Lieksa-4 consisted of unusually high amounts of P, so the object was tentatively considered man-made, and the studies were brought to a halt. The suspected meteorite was then sent to Geohouse in Turku, Finland for further study.

Lieksa-4 is about 3.5 cm in diameter, and its total mass at the time of discovery was 163.7 g (Moilanen, 2018). The polished surface of the endcut is highly reflective which makes it appear light in colour, and it consists of several fractures along the surface plane (Figure 1). The texture consists of round, ≤ 0.5 mm granules in a much finer grain-size matrix. A few larger, ~ 3 mm granules occur on the polished endcut. The meteorite has no visible fusion crust, and nothing is known about its fall. The outer layers of the meteorite show significant signs of weathering (class C), suggesting that it has been on the ground for an extended period.

The aim of this research is to determine the mineralogy, geochemistry, and texture of Lieksa-4, and to attempt to classify it based on these data.

2. Methods

Several research methods were utilized to reveal the nature of Lieksa-4. A corner of the meteorite was cut off and the endcut was polished. The cut off piece was divided into four parts. Part of it was pulverised and separated into two different fractions: metallic hard granules, and soft matrix. The two pulverised fractions were analysed by X-ray diffraction (XRD) at the University of Turku. In addition, an epoxy-mounted polished section, and a steel plate-mounted unpolished section were made. The pieces were investigated under the optical microscope and analysed with scanning micro-X-ray fluorescence (μ-XRF) and field emission scanning electron microscope equipped with an energy dispersive X-ray spectrometer (SEM-EDS) at the

University of Turku, and with laser ablation inductively coupled plasma mass spectrometry (LA-SC-ICPMS) at the Geological Survey of Finland, Espoo.

Figure 1. The endcut of Lieksa-4 showing its reflective material and the internal structure. The meteorite consists of small (≤ 0.5 mm), round granules with a few larger (~ 3.0 mm) granules present as well. The outer layer is covered in a thick (~ 1 mm) layer of rust, suggesting that Lieksa-4 has been on the ground for an extended period.

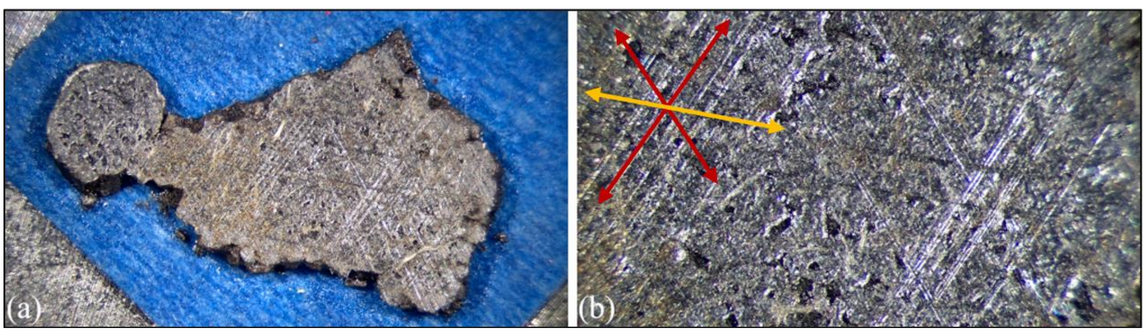

Figure 2. The unpolished section of Lieksa-4, showing the Neumann deformation lines. (a) 0.63x and (b) 2.5x magnifications. The lines seen here occur in at least 3 different directions, with two main directions (highlighted with red arrows in b) that form 110° and 70° angles relative to each other. A third set of lines (highlighted with a yellow arrow in b) occur in 60° and 50° angles relative to the main set of lines.

3. Results

The microscopic study revealed several crosscutting lines, most obvious on the unpolished section (Figure 2). They are similar to the Neumann deformation lines observed in several iron meteorites (e.g., Buchwald 1975).

The XRD analyses of the round granules show X-ray diffraction pattern corresponding to kamacite (α-(Fe, Ni)), while the matrix consists of schreibersite ($(Fe,Ni)_3P$) and minor amounts of troilite (FeS).

The SEM-EDS analyses suggest that kamacite constitutes roughly 70 wt% of the meteorite, schreibersite 20 wt%, and troilite ≤ 1 wt%. In addition, various types of kamacite exsolution can be seen in schreibersite throughout the sample (Fig. 3).
The LA-SC-ICPMS analysis was carried out successfully only on the kamacite granules, since the schreibersite grains were far too small for a 50 µm spot size needed to get adequate LOD on the critical elements Ir and Ge. Trace amounts of several elements common to iron meteorites were detected in both the SEM-EDS and LA-SC-ICPMS analyses (Table 1).

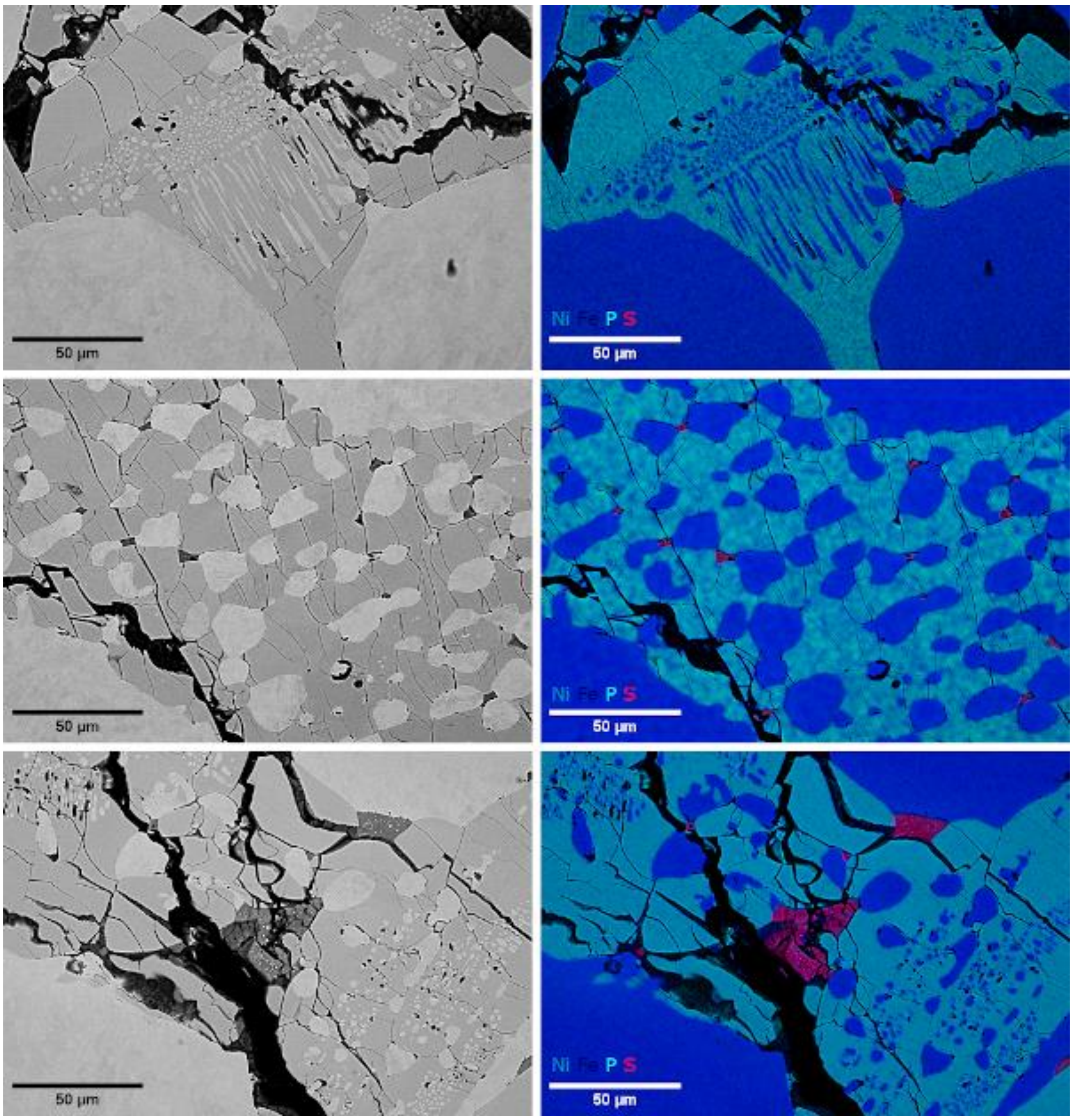

Figure 3. Backscattered electron micrographs and elemental maps showing the details of the kamacite exsolution. Dark blue areas represent kamacite, light blue schreibersite. Magenta areas correspond to troilite. The exsolution occurs in different textures and greatly varying sizes from sub-micron size globules to elongated, several tens of microns long patches. Troilite occurs always angular in the schreibersite-matrix, and it contains often sub-micron size inclusions of an unidentified material.

Table 1. The results of Lieksa-4 composition using LA-SC-ICPMS and SEM-EDS methods. The results are rounded upwards. All results in ppm, except for Fe, Ni, P, Co, and S which are in wt%.

Method	Fe	Ni	P	Co	S	Ir	Ga	Ge	Au	V	Cr
LA-ICP-MS*	85	10		< 1		2	11	5	< 1	< 1	300
FE-SEM	83	11	4	< 1	< 1						400

*Results obtained solely from the kamacite phase.

4. Discussion

Optical study of Lieksa-4 shows Neumann lines on the sample. These are believed to represent shock-induced, severe structural deformation of the kamacite lamellae (e.g., Buchwald, 1975). The XRD analysis shows that the sample consists of kamacite and schreibersite, with minor amounts of troilite. The FE-SEM analysis shows that the kamacite phase occurs in two different forms: (1) round, ≤ 0.5 mm granules; and (2) small, several tens of microns to sub-micron wide and tens of micros long lamellae in the matrix. LA-SC-ICPMS analysis of the kamacite granules detected minor amounts of Au, Ga, Ge, and Ir. Overall, the meteorite consists of approximately 84 wt% Fe, 11 wt% Ni, 4 wt% P and > 1 ppm S. These results clearly suggest that Lieksa-4 is an iron meteorite.

The compositional and textural features of the Lieksa-4 meteorite suggest the following solidification scenario: 1) nucleation and rapid growth of the round macroscopic kamacite granules from a P-rich parent melt; 2) exsolving of phosphate liquids from the residual liquid; 3) crystallisation of the schreibersite matrix and exsolution of the microscopic kamacite; 5) final crystallisation of troilite from the residual iron sulphide. The crystallisation of the schreibersite phase likely took place at lower temperatures compared to the kamacite phase. The kamacite within the schreibersite-matrix then formed as a result of exsolution phenomena.

Based on its chemical and structural features, Lieksa-4 does not fit into any of the existing iron meteorite classes. Thus, the meteorite should be classified as an anomalous iron meteorite for now (Kotomaa, 2022).

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